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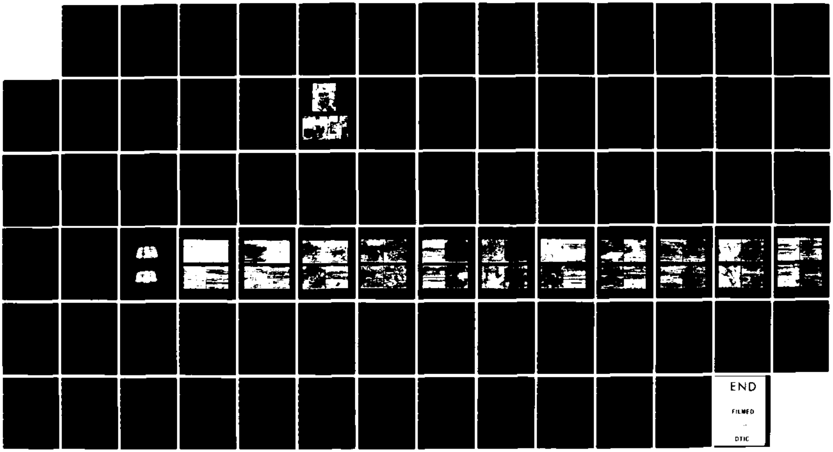

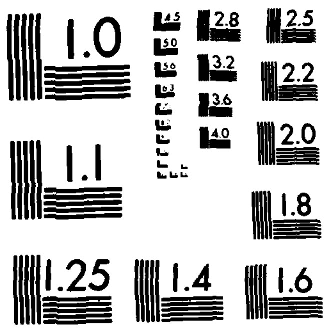

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MAY 1984

PERFORMANCE EVALUATION OF AUTOMOTIVE WHEEL BEARING GREASES

FINAL REPORT

SKF INDUSTRIES, INC. REPORT NO. AT84T004

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FOR

U. S. ARMY MOBILITY EQUIPMENT
RESEARCH AND DEVELOPMENT COMMAND
FORT BELVOIR, VIRGINIA

SKF TECHNOLOGY SERVICES
SKF INDUSTRIES INC
KING OF PRUSSIA, PA

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The lubrication characteristics of five candidate greases for use in non-driven wheel bearings of U.S. Army vehicles have been experimentally evaluated. The lubrication capability of each grease was established in a laboratory environment on a machine designed to simulate the general configuration of an automotive front wheel bearing hub under highly accelerated

test conditions designed to precipitate a lubricant related bearing failure. A pair of tapered roller bearings of the size typically used in an automotive application were run at an inner ring speed of 800 rpm, equivalent to 105 kph, and loaded under a continuous radial force equivalent to 150% of the vehicle curb weight and cyclic axial cornering force equal to 30% of the radial force applied for 1-1/2 minutes out of every 5. The ambient environment was also artificially elevated to 394 K (121^{o} C) to further accelerate the test cycle.

Visual post test examinations were conducted to establish (a) the amount and condition of the residual grease remaining on each bearing, and (b) the extent of the damage to the rolling contact surfaces. This was augmented with the examination of representative bearings employing a Scanning Electron Microscope (SEM) to define the degree of micro-deterioration experienced on the rolling contact surfaces.

Each lubricant was rated on the basis of the experimental life achieved, the condition of the residual grease within the bearings and the condition of contact surfaces. The performance of these greases was subsequently compared to that of greases tested in previous programs.

SUMMARY

The lubrication characteristics of five candidate greases for use in non-driven wheel bearings of U.S. Army vehicles have been evaluated. The lubrication capability of each grease was established in a laboratory environment under highly accelerated test conditions designed to precipitate a lubricant related bearing failure.

Tests were conducted on a machine designed to simulate the general configuration of an automotive front wheel bearing hub. A pair of tapered roller bearings of the size typically used in an automotive application were run under a combined radial and thrust load at an inner ring speed of 800 rpm, equivalent to 105 kph. The hub was loaded under a continuous radial force equivalent to 150% of the vehicle curb weight and an additional cyclic axial cornering force equal to 30% of the radial force was applied for 1-1/2 minutes every 5 minutes. In addition, the hubs were run in an ambient environment artifically elevated to 394 K (121° C) to further accelerate the test cycle. The bearings were run to failure or 300 hours. Ten sets of bearings were run with each grease.

Post test visual observations were made on each set of bearings to establish (a) the amount and condition of the residual grease remaining on each bearing, and (b) the extent of the damage to the rolling contact surfaces.

A sample of representative bearings from each group were studied in greater detail employing a Scanning Electron Microscope (SEM) in order to define the degree of deterioration experienced on the rolling contact surfaces. Photomicrographs from the SEM show the changes to the surface morphology of typical cone rolling contact surfaces of each grease tested.

The experimental L_{10} life of each test group was statistically estimated using a maximum likelihood technique assuming the existence of a Weibull distribution of the data.

Each lubricant was rated on the basis of the experimental L_{10} life achieved, and the post test observations made on the condition of the grease within the bearings and that of the rolling and sliding contact surfaces.

On the basis of these tests the greases were ranked as follows:

GREASE	RANK
E [3]	Poor
A [3]	Poor
C [3]	Poor
B [3]	Poor
D [3]	Fair

In relationship to the performance of other greases tested previously, Greases E [3], A [3] lubricate comparably to baseline Greases A [1] and B [1] which were also ranked poor. The later greases conform to Mil-G-10924C and are currently used by the Army to lubricate wheel bearings. Although these greases are probably adequate for normal operational conditions, the results indicate that under sustained high ambient temperature conditions (as tested herein) they deteriorate rapidly, thereby compromising lubrication efficiency.

Greases C [3] and B [3] faired better but still are considered inadequate for high temperature operation. Grease D [3], although the best performer of the five greases evaluated was marginal and may also lack the required stability to lubricate under the highly rigorous and hostile environmental conditions expected to be encountered in Army vehicle service.

PREFACE

This report presents the results of a study conducted by SKF Technology Services for the U.S. Army Mobility Equipment Research and Development Command, Fort Belvoir, Virginia, 20060 under Contract No. DAAK70-83-C-0063. This report encompasses effort conducted from August 1983 to May 1984.

Technical direction for the U.S. Army was provided by Mr. James Beeson, the Contracting Officers Representative and Dr. Insik Rhee.

The principle investigators from the SKF Mechanical Laboratories responsible for the conduct of this project were:

Mr. N. J. Ninos - Scientist and Project Leader

Mr. F. R. Morrison - Section Supervisor under whose direction the work was accomplished.

Mr. D. Hahn - Technician conducting the Scanning Electron Microscope studies

Mr. G. Barr - Technician conducting the tests.

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1.0 INTRODUCTION

1.1. Objective

The objective of this exploratory effort is to establish the relative performance characteristics of candidate multi-purpose military greases for use in non-driven wheel applications used in U.S. Army automotive motor vehicles.

1.2 Background

The study reported herein is the third in a series aimed at evaluating greases utilized by the U.S. Army for automotive wheel bearing applications procured under Military Specification MIL-G-10924C. Of some concern is the feasibility of utilizing the greased-for-life wheel bearing concept and the ramifications resulting from such action.

Two grease evaluation programs have now been conducted for the Mobility Equipment Research and Development Command (MERADCOM) under U.S. Army contracts [1 and 2]. The tests provided a data base on the relative lubrication capabilities of a number of greases which could be utilized in automotive front-wheel bearing applications. Six greases were evaluated in Phase I, i.e. one commercial product, and five greases conforming to certain military specifications. Five additional MIL-G-Spec greases were evaluated in Phase II to establish their lubrication efficiency.

1.3 Scope

The program that is the subject of this report, Phase III, is a logical extension of that effort. The current tests expand the data base to include a broader range of grease types. MERADCOM selected and provided the following five greases:

[1] Phase I - MERADCOM DAAK70-77-C-0034
[2] Phase II - MERADCOM DAAK70-79-C-0213

Test Grease	Test Bearing - Grease Series
A[3]	688-100
B[3]	688-200
C[3]	688-300
D[3]	688-400
E[3]	688-500

[3] Phase III - MERADCOM DAAK70-83-C-0063

1.4 Method of Approach

To facilitate the evaluation of the lubrication characteristics of a grease, accelerated life tests were conducted employing paired tapered roller bearings as test specimens. The bearings were mounted in a wheel hub configuration simulating a typical automotive front wheel application. The test specimens were standard production bearings of the LM12749/LM12710 and L68149/L68110 designation produced by the Tapered Bearings Division of SKF Industries, Inc.

To obtain a sufficient amount of data within a practical period of time, testing was accelerated by applying loads of a higher magnitude than would normally be applied in automotive service; and by artifically elevating the ambient temperature surrounding the hub assembly.

The bearings were run either to failure or to a time up life of 300 hours, which represents 14.4 million revolutions or 32,000 kilometers of operation. The theoretical L_{10} life of the system, i.e. both bearings is 11.2 million revolutions as shown by the calculations in Appendix I.

In this study ten pairs of bearings (ten each LM12710 and L68100 series tapered roller bearings) were run with each grease sample in order to obtain a data base from which the experimental L_{10} life of the population could be determined.

All bearings were examined visually at the conclusion of the test at magnifications up to 30X. Of interest was the condition of the residual grease in the bearings and the extent of damage to the rolling contact surfaces.

In addition, the rolling contact surfaces of cones from two pairs of the highest lived bearings lubricated with each test grease were examined in greater detail using a Scanning Electron Microscope (SEM). The surfaces were examined at high power (250 and 1000X magnification) to detect the extent of the physical damage to the cone rolling contact surfaces. Photomicrographs taken with the SEM, serve to document the surface morphology for comparison with photomicrographs from previous investigations.

Accordingly, the running surfaces of the cones were examined and the degree of microwear and other surface damage characteristics established for each type grease. This additional information supports the experimental L_{10} life value which is the primary basis of evaluation of a lubricants functional capability. The greases were then rated relative to one another according to all of the above parameters. The rating can be used to predict the performance of a grease in a nondriven wheel application operating in an extreme temperature and rigorous environment.

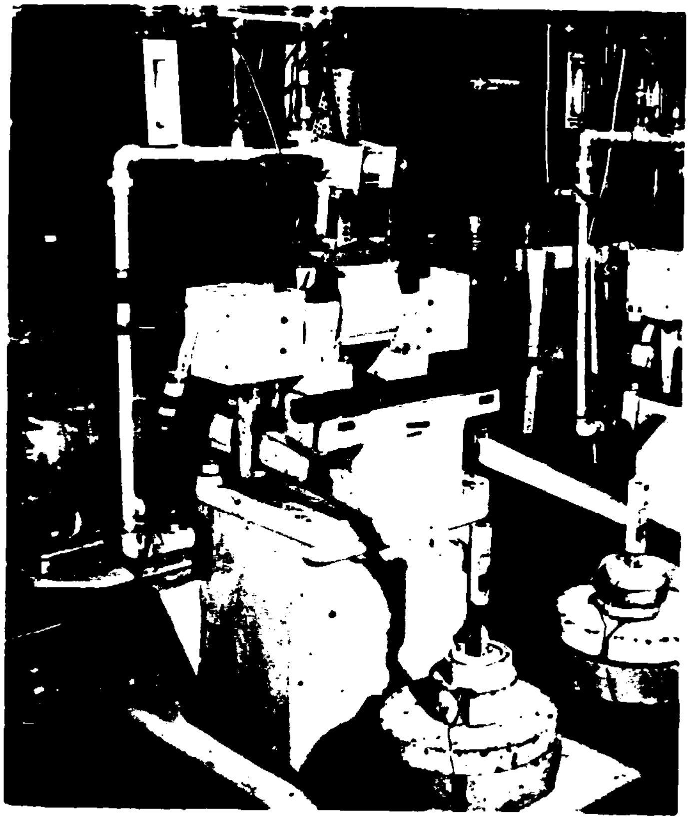
2.0 INVESTIGATION

The tests were conducted on a basic SKF Industries, Inc. R-2 Endurance Test Machine which was modified to accept a simulated nondriven front wheel hub assembly. Each hub housed LM12749/LM12710 (outboard) and L68149/L68110 (inboard) tapered roller bearings which were used as test specimens. The lubricating efficiency of a grease was based on the endurance life of the bearing set. A detailed description of the design and operation of this test machine, the test procedures and the conditions under which the tests were performed are presented in the following sections.

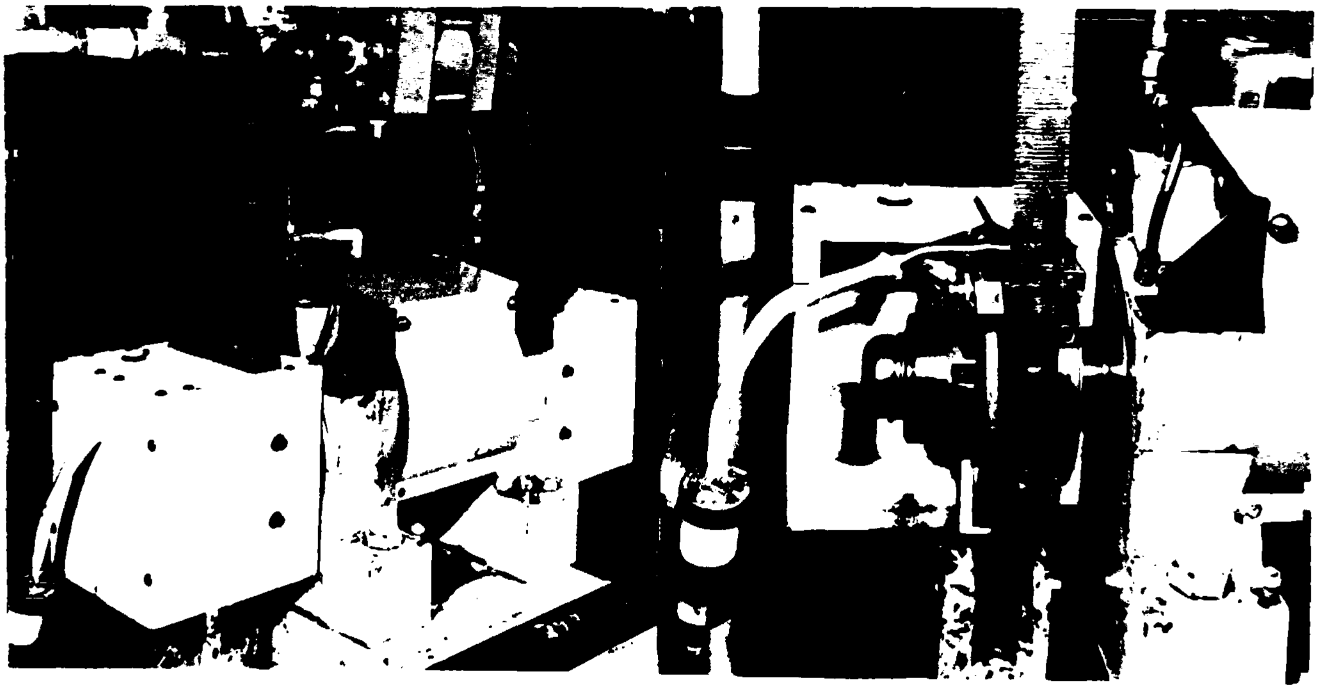
2.1 Endurance Test Machine

The basic configuration of the test machine consists of a centrally belt driven horizontal arbor which is supported by two cylindrical roller bearings. Photographic views of the machine are shown in Figure 1. A hub containing a pair of tapered roller bearing test specimens is mounted on each end of the arbor as shown in the assembly drawing of Figure 2. A constant radial force is applied to each hub assembly by a dead weight through a lever and linkage arrangement. A thrust force is applied inward by an air cylinder mounted between the hubs at a prescribed distance from the bearing axis. This offset simulates a cornering force on the hub assembly as would be produced at the tire periphery when a car turns. The thrust force is applied cyclically every five minutes for 1-1/2 minutes duration.

The bearings were run in an artifically heated environment created by a Chromalox 500 Watt ring heater, fastened to the side of the load arm, and surrounding the hub as shown in Figure 2. The heater provided the additional heat, over and above that caused by internal bearing friction, to bring the bearing temperature to the required level of operation. Power to the dual element heater was adjusted manually through a Powerstat. One element of the heater was on constantly and supplied that amount of heat needed to bring the operating temperature of the test bearings to within 10 to 15 K of the specified level. The second element, powered through the same Powerstat, and automatically controlled by a Chromalox temperature controller maintained the bearing temperature at the prescribed



(a) Overall View



(b) Enclosed Test Head (c) Test Hub and Heater

Figure 1. Photographs of Front Wheel Bearing Test Machine

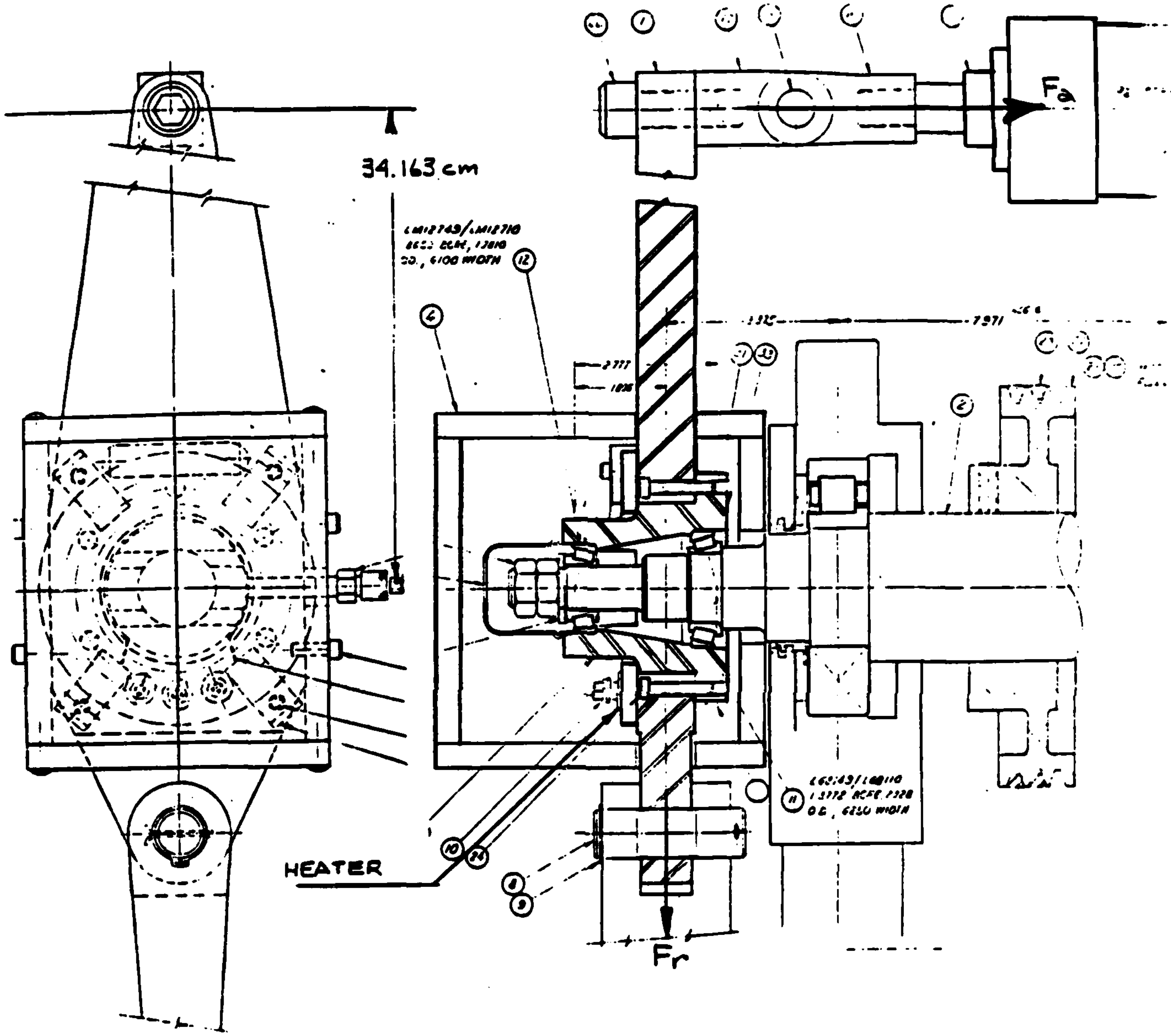


Figure 2. Schematic of Hub Assembly Front Wheel Bearing Grease Test Machine

operating level. An insulated housing, Figure 2, surrounding each hub assembly helped to contain the heat at an even level and prevented rapid thermal fluctuations.

The operating temperature of each bearing was measured by an iron-constantan thermocouple in contact with the outer ring (cup) outer diameter surface. The operational temperature of the inner (LM68100) bearing was indicated and monitored by a Chromalox Temperature Controller that also actuated the heater required to operate the system at the designated temperature level. The operational temperature of the outer (LM12700) bearing was recorded by an Easterline Angus Strip Chart Recorder and by the SKF test floor computer whose function was to stop the test if the operational temperature exceeded the preset temperature limit of 403K (130^{o}C).

2.2 Test Procedure

2.2.1 Test Bearing Description

The lubricating capability of each grease was determined using bearings of the following configuration as test specimens.

Bearing No.	Bearing Size mm			
	Inner Diameter	Outer Diameter	Width	Location on Test Arbor
LM12749/LM12710	21.979	45.974	15.494	Outboard
L68149/L68110	34.981	59.974	15.875	Inboard

These bearings were a statistically similar sample group produced according to SKF Industries, Inc. manufacturing standards and tolerances for material and geometry.

2.2.2 Test Bearing Preparation and Lubrication

Each set of bearings was cleaned in a bearing washer with Union 76 Corp. 460 Solvent and blown dry with air. The bearings were then packed full with the test grease and installed in the hub. An additional 40 grams of grease was distributed in the hub cavity between the bearings. The hubs were then installed on the test rig spindle and the axial looseness adjusted from 15 to 30 μm.

2.2.3 Test Conditions

The following test conditions were common to all tests and are based upon an industrial method used to evaluate the endurance of commercial wheel bearings. In this test procedure, a hub assembly is subjected to a radial load equivalent to 150% of the vehicle curb weight. In addition, a thrust load, or cornering load equal to 30% of the radial load is applied intermittently at a distance from the center of the bearing axis which is equivalent to the tire radius.

On the basis of the weight of a medium size sedan, the bearings were subjected to a constant radial load of 8.34 kN (1875 lbs.f). In addition, a thrust load of 2.49 kN (560 lbs.f) was applied at a distance of 34.2 cm (13.45 inches) from the horizontal centerline of the bearing axis every 5 minutes for a duration of 1-1/2 minutes or 30% of the time.

The bearings were run at an inner ring speed of 800 rpm which is approximately equivalent to a vehicle speed of 105 kph (65 mph).

The bearing operational temperature was controlled at 394 $\pm$ 2K.

Three test rigs were employed in order to complete this study in a reasonable time interval.

A group of ten pairs of test bearings were run with each test grease.

2.2.4 Test Termination Criteria

A test was run until either one of the bearings failed as described below or after 300 hours (time up) of operation. A 300 hour run is equivalent to 14.4 million revolutions or approximately 32,000 kilometers (20,000 miles).

A test was terminated if:

a) Bearing failure caused the level of vibration to exceed a preset limit. A Vibraswitch mounted on the test rig stopped the test automatically.

b) The operational temperature exceeded a preset limit (403K) due to a thermal imbalance caused by a temperature acceleration of one of the test bearings.

c) The electrical power required by the heaters to maintain the operating temperature at 394K decreased to 50% of the original amount. This denotes an increase in the amount of heat generated by the bearings themselves resulting from an increase in friction as the result of inadequate lubrication.

2.3 Post Test Observations

At the conclusion of a test, each bearing specimen was examined visually to assess the quantity and condition of the grease remaining in the bearing. In addition, each bearing was disassembled to examine the rolling contact surface of the cup and cone. The surfaces were examined visually and optically with up to 30X magnification to assess the specific damage that had occurred, and to establish the mode of failure.

Furthermore, the morphology of the cone rolling contacts from two sets of bearings which had run the longest with each grease was examined with a Scanning Electron Microscope at 250 and 1000X magnification. This investigation was done to establish the extent of wear and surface distress present, which are an indication of grease lubrication efficacy.

3.0 TEST RESULTS

The method of rating a grease according to its ability to lubricate a tapered roller bearing in an environment such as a non-driven front or rear automotive wheel has been established in previous investigations. On that basis lubricants relative efficiency was judged according to the following parameters:

1. The experimental L_{10} life achieved by a group of bearings lubricated by the test grease.
2. The severity of grease deterioration.
3. The ability of the lubricant to protect the rolling contact surface morphology.

3.1 Wheel Bearing Grease Tests - Post Test Observations

Post test observation details are presented in Tables I to V. The tables, in general describe the quantity and condition of the grease remaining on the running surfaces, the damage to the rolling contacts, the number of hours each bearing ran and the reason for terminating the test.

TABLE I

TYPE I TEST - GREASE A [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
102	104 (5.0)	Fair Resid.Grease Film Mod. Oxid. Dark Brown	Poor Cone - Macro Spall	124	Good Resid.Grease Film Light Oxid.	Fair O.K.	125	LM12700 Cone Spalled
103	188 (9.0)	Fair Resid.Grease Film Mod. Oxid. Dark Brown	Fair O.K.	120	Good Resid.Grease Film Light Oxid.	Fair Cup Spalled	124	L68100 Cup Spalled
104	188 (9.0)	Poor Resid.Grease Film	Poor Cone Spalled	120	Good Resid. Grease Film	Fair Cup Spalled	122	LM12700 Cone Spall L68100 Cup Spall
105	160 (7.7)	Fair Resid.Grease Film Mod. Oxid. Dark Brown	Fair O.K.	120	Good Resid.Grease Film Light Oxid.	Fair Cup Spalled	120	L68100 Cup Spalled
106	160 (7.7)	Fair Resid.Grease Film Mod. Oxid. Dark Brown	Fair O.K.	120	Good Resid.Grease Film Light Oxid.	Poor Cone Spalled	119	L68100 Cone Spalled

TABLE I continued

TYPE I TEST - GREASE A [3]

DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP.Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP.Temp°C	Reason for Test Termination
108	176 (8.4)	Poor Resid.Grease Film Mod. Oxid. Dark Brown	Fair O.K.	120	Good Resid.Grease Film Light Oxid.	Poor Cone Spall	126	L68100 Cone Spalled
110	213 (10.2)	Poor Resid.Grease Film Oxid. on contacts, Dark Brown	Poor Cone Spall	120	Fair Resid.Grease Film Mod. Oxid.	Poor Cup Spalled	126	LM12700 Cone Spall L68100 - Cups Spall
101	292 (14.0)	Poor Resid.Grease Oxid. on contacts, Dark Brown	Poor Cone Spalled	122	Fair Resid. Grease Film Mod. Oxid.	Poor Cup & Cone Spalled	122	LM12700 Cone Spall L68100 Cup & Cone Spall
107	293 (14.0)	Poor Resid.Grease Oxid. Dark Brown	Poor - Gross Cone Spalled Side to Side 360°	118	Fair Resid.Grease Film Mod. Oxid.	Poor - Gross Cone - Spalled Cup - Small Spall	119	LM12700 Cone Spall L68100 - Cone Spall
109	281 (13.5)	Poor Resid.Grease Oxid. Dark Brown	Poor Cone Spalled	119	Fair Resid.Grease Film Mod. Oxid.	Poor Cone Spalled	120	LM12700 Cone Spall L68100 - Cone Spall

TABLE II

TYPE I TEST - GREASE B [3]

DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
201	236 (11.4)	Poor Dry, Sparse Dark Brown Very Oxid.	Fair Carb.Grease Res. on Roll.Cont.Surf. Caused Noise	124	Poor Dry, Sparse Dark Brown Very Oxid.	Fair Trace Resid.Oil Contacts Light Brown Disc	124	Lub. Failure Noisy Operation
202	185 (8.9)	Poor Sparse Mod. Oxid. Dark Brown	Poor Cup & Cone Spalled, Trace Res. Oil	124	Poor Dry Sparse Very Oxid. Dark Brown	Fair Trace Resid. Oil Contacts Light Blue-Brn Disc	122	LM12700 Cup & Cone Spall
203	358 (17.2)	Poor Sparse Very Oxid. Black	Poor Very Dry Cont. Light Brown	126	Poor Dry, Sparse Carbon Matl. Black	Poor Very Dry Cont. Brown	125	Suspended Lub Failure
204	142 (6.8)	Poor Sparse Mod. Oxid. Dark Brown	Fair Trace Res. Gr. + Oil Brown Disc.	122	Poor Very Dry and Oxid Carbon Matl. Black	Poor Very Dry Cont. Brown	122	Lub Failure Cup Spalled
205	320 (15.5)	Poor Sparse Very Oxid. Black	Poor Black Carbon Deposit on Contacts	127	Poor Very Dry & Oxid.	Poor Very Dry Carbon Deposit on Contacts	128	Suspended Lub Failure
206	250 (12.0)	Poor Sparse Very Oxid Dark Brown	Poor Dry Cone Spall	126	Poor Very Dry & Oxid. Black	Poor Cone Spalled Very Dry Black Carbon Deposit on Contacts	126	Lub Failure L68100 Cone Spall

TABLE II continued

TYPE I TEST - GREASE B [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
207	119 (5.7)	Good Oily Slt. Oxid. Dark Brown	Poor Cup Spalled Resid. Oily Grease	124	Good Oily Slt. Oxid. Dark Brown	Fair Resid. Oily Grease Brown Disc	128	Lub Failure L68100 Cup Spall Noisy Operation
209	309 (14.9)	Poor Dry, Sparse Very Oxid. Black	Poor Very Dry Races Discolored	120	Poor Dry,Sparse Very Oxid. Dark Brown	Poor Cup & Cone Spall Black Carbon Deposit on Races	120	L68100 Cup & Cone Spall Lub Failure
213	238 (11.4)	Poor Dry, Sparse Very Oxid. Black	Poor Black Carbon Deposit on Races	123	Poor Dry, Sparse Very Oxid. Black	Poor Very Dry Carb. Deposit Races	123	Lub Failure
217	95 (4.6)	Poor Sparse Very Oxid. Black	Poor Heat Discolored Dry	122	Poor Dry, Sparse Very Oxid. Black	Poor Cup Spalled Very Dry Races Heat Disc.	122	Lub Failure L68100 Cup

TABLE III

TYPE I TEST - GREASE C [3]

DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
301	141 (6.8)	Fair Greasey Sparse Mod. Oxid. Dark Brown	Poor Cone Spalled Free Oil on Contacts	119	Good Very Greasy Light Brown Very Oxid.	Fair O.K. Brown Disc	121	Lub Failure LM12700 Cone Spall
302	265 (12.7)	Poor Dry-Very Oxid. Black Carbon Dep.	Poor Cone Spalled Dry, Contact Very Hot	121	Fair Almost Dry Mod. Oxid. Dark Brown	Fair Cone Spalled Dry Contacts Brown	121	Lub Failure & Cone LM12700 - Spalled Overheated L68100 - Spalled
303	130 (6.2)	Poor Fairly Greasy Mod. Oxid. Dark Brown	Poor Overheated Heat Discolor Dry	121	Fair Resid. Grease Mod. Oxid. Dark Brown	Fair Contact Trace Brown	121	Lub Failure LM12700 - Overheated
304	130 (6.2)	Poor Dry - Very Oxid. Black Carbon Deposit	Poor Contacts Surf. Spalled, Dry Heat Discolor.	122	Fair Greasy Mod. Oxid. Dark Brown	Poor Cone Fract.	121	Lub Failure LM12700 - Overheated L68100 Fractured
305	355 (17.0)	Poor Dry - Very Oxid. Black Carbon Deposits	Poor Contacts Surf. Spalled, Dry Heat Discolor	120	Poor Dry Mod. Oxid. Dark Brown	Fair Trace Heat Discolor. Dry	121	Suspended LM12700 - Overheated Lub Failure
306	190 (9.1)	Poor Dry - Very Oxid. Black Carbon Deposits	Poor Cone - Many Spalls Dry & Heat Discolor	121	Fair Almost Dry Dark Brown	Fair Trace Heat Discolor Dry	121	Lub Failure LM12700 Spalled & Overheated

TABLE III continued

TYPE I TEST - GREASE C [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
307	192 (9.2)	Poor Dry - Very Oxid. Black Carbon Deposit	Poor Cone - Severly Spalled Dry	120	Fair Almost Dry Mod. Oxid Dark Brown	Fair Dry Trace Heat Discolor	121	Lub Failure LM12700 - Spalled
308	207 (9.9)	Poor Dry-Very Oxid. Black	Poor Cone Spalled Dry	119	Fair Almost Dry Mod. Oxid. Dark Brown	Fair Dry Trace Heat Discolor	121	Lub Failure LM12700 Spall
310	167 (8.0)	Poor Almost Dry Mod. Oxid. Dark Brown	Poor Cone - Macro Spalled Light Discolor	120	Fair Mod. Oxide Med. Brown	Fair Trace Heat Discolor	121	Lub Failure LM12700 Cone Micro Spalled
311	193 (9.2)	Poor Dry - Mod. Oxid. Dark Brown	Poor Cone - Large Spall	119	Fair Resid. Oil Light Oxid. Med. Brown	Fair O.K.	121	Lub Failure LM12700 Spall

TABLE IV

TYPE I TEST - GREASE D [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	Reason for Test Termination
401	329 (15.8)	Poor Dry - Very Oxid. Dark Brown	Fair Carb. Dep. Lt. Discolor	121	Poor Dry Very Oxid. Dark Brown	Good Trace Resid. Oil, No. Disc.	121	Suspended
402	143 (6.9)	Poor Dry-Very Oxid. Dark Brown	Poor Cone - Minute Spalls Heat Disc	123	Poor Mod. Resid.Gr. Dark Brown	Poor Cup & Cone Spall Heat Disc.	121	Lub Failure LM12700 Cone L68100 Cup - Cone Spall
403	190 (9.1)	Fair Greasy - Mod.Oxid Resid. Grease Dark Brown	Poor Cone-Spalled Heat Discolor	122	Fair Greasy Mod.Oxid. Resid. Grease	Poor Cup-Spalled	121	Lub Failure LM12700 Cone L68100 Cup
404	304 (14.6)	Fair Greasy - Mod.Oxid. Resid. Grease Dark Brown	Fair O.K.	122	Fair Greasy - Mod. Oxid Resid. Grease Dark Brown	Fair O.K.	121	Suspended
405	205 (9.9)	Fair Greasy -Mod Oxid. Resid. Grease Dark Brown	Fair O.K.	120	Fair Greasy - Mod. Oxid Resid. Grease Dark Brown	Fair Cup - Spall	121	L68100 Cup Spall

TABLE IV continued

TYPE I TEST - GREASE D [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. Brg. OP. Temp°C	Reason for Test Termination
406	186 (9.0)	Fair Resid. Grease Mod. Oxid. Dark Brown	Poor Cone Spall	122	Good Resid. Grease Greasy Mod. Oxid. Dark Brown	Fair O.K.	121	Lub Failure LM12700 Cone Failure
408	135 (6.5)	Fair Resid. Grease Mod. Oxid. Dark Brown	Fair O.K.	122	Fair Resid. Grease Mod. Oxid Dark Brown	Poor Cup & Cone Spall	121	Lub Failure L68100 Cone & Cup Spall
407	252 (12.1)	Fair Resid. Grease Mod. Oxid. Dark Brown	Fair O.K.	121	Fair Resid. Grease Mod. Oxid. Dark Brown	Poor Cone Spall	121	Lub Failure L68100 Cone Spall
411	204 (9.8)	Poor Dry - Very Oxid. Black	Poor Cone Spall	122	Fair Resid. Grease Mod. Oxid. Dark Brown	Fair O.K.	121	Lub Failure LM12700 Cone Spall
414	233 (11.2)	Poor Dry - Very Oxid. Black	Poor Cone Spall Heat Discolor	120	Poor Dry - Very Oxid. Black	Poor Cup & Cone Spall Heat Discolor	121	Lub Failure L68100 Cup & Cone Spall LM12700 Cone Spall

TABLE V

TYPE I TEST - GREASE E [3]
DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	Reason for Test Termination
501	226.1 (10.9)	Poor Dry - Resid.Grease Black - Very Oxid.	Poor Cone & Cup Minute Spalls	123	Poor Dry Resid. Grease Black - Very Oxid.	Fair Minute Spall	121	Lub Failure LM12700 Cone Spall
502	70.0 (3.4)	Poor Sparse Grease Tan	Fair	126	Poor Sparse Grease Tan	Fair O.K.	121	Lub Failure Temp. Excursion Spall
503	156.1 (7.5)	Poor Resid. Grease Dry, Black Very Oxid.	Fair Cone-Trace Carb. Deposit	125	2air Resid. Grease Tan, Mod. Oxid.	Fair O.K.	121	Lub Failure Temp. Excursion
504	120.0 (5.8)	Poor Resid. Grease Tan - Mod. Oxid.	Fair Cone - Trace Carb. Deposit	124	Fair Very Sparse	Fair O.K.	121	Lub. Failure Temp. Excursion
505	53.2 (2.6)	Poor Resid. Grease Dry, Black Very Oxid.	Fair Cone - Trace Carb. Deposit	118	Fair	Fair O.K.	121	Lub. Failure Temp. Excursion
506	87.5 (4.2)	Poor Resid. Grease Dry, Black Very Oxid.	Poor Cone - Trace Macro Spall	119	Fair	Fair O.K.	121	Lub. Failure Temp. Excursion

TABLE V continued

TYPE I TEST - GREASE E [3]

DETAILS OF FRONT WHEEL BEARING GREASE TESTS AND OBSERVATIONS

Brg. Set No.	Hours Run (MR)	OUTBOARD BEARING LM12700 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	INBOARD BEARING L68100 Lubricant Condition	Bearing Condition	Avg. OP. Brg. Temp°C	Reason for Test Termination
507	166.3 (8.0)	Poor Resid. Grease Black - Mod. Oxid	Fair Cone-Black Carb. Deposit	123	Fair	Fair O.K.	121	Lub. Failure Temp. Excursion
509	94.2 (4.5)	Poor Resid. Grease Dry, Dark Brown Very Oxid.	Fair Cone - Black Carb. Deposit	118	Poor Dry	Fair O.K.	121	Lub Failure Temp. Excursion Spall
511	89.6 (4.3)	Poor Resid. Grease Dry, Dark Brown Very Oxid.	Fair Cone-Black Carb. Deposit	120	Fair Tan, Mod. Oxid.	Fair O.K.	121	Lub Failure Temp. Excursion
513	70.7 (3.4)	Poor Resid. Grease Dry, Dark Brown Very Oxid.	Fair O.K.	121	Fair	Fair O.K.	121	Lub. Failure Temp. Excursion

3.2 Endurance Test Results and Statistical Analysis

The life data of each bearing-grease group has been statistically treated employing an SKF developed maximum likelihood computer program [4]. The program establishes the L_{10} and L_{50} lives and 90% confidence interval estimates for each, as well as the slope of the experimental Weibull distribution. The results of this analysis in terms of millions of revolutions are presented in Tables VI to X.

Explanation of Tabular Notations

LCL - Lower Confidence limit @ 90% Confidence Level
UCL - Upper Confidence limit @ 90% Confidence Level
Med L_{10} - Median bias corrected 90% reliable life
Med L_{50} - Median bias corrected 50% reliable life
Beta - Weibull shape parameter or slope

TABLE VI

ENDURANCE TEST RESULTS AND STATISTICAL ANALYSIS

FT. BELVOIR GREASE A[3]

TYPE I TEST - 394K BEARING OPERATING TEMP

Bearing Life - Millions of Revolutions

5.0	F
7.7	F
7.7	F
8.4	F
9.0	F
9.0	F
10.2	F
13.5	F
14.0	F
14.0	F

Bearing Life - Millions of Revolutions

LCL L_{10}	MED L_{10}	UCL L_{10}
0.88	2.68	5.88
LCL L_{50}	MED L_{50}	UCL L_{50}
6.25	10.40	16.10

SLOPE BETA
1.506

F = Failed
S = Suspended

F-4185C-1-R100

TABLE VII

ENDURANCE TEST RESULTS AND STATISTICAL ANALYSIS

FT. BELVOIR GREASE B[3]

TYPE I TEST - 394K BEARING OPERATING TEMP

Bearing Life - Millions of Revolutions

4.6	F
5.7	F
6.8	F
8.9	F
11.4	F
11.4	F
14.9	F
12.0	F
15.4	S
17.2	S

Bearing Life - Millions of Revolutions

LCL L_{10} 1.83	MED L_{10} 4.52	UCL L_{10} 7.21
LCL L_{50} 7.93	MED L_{50} 10.96	UCL L_{50} 15.47

SLOPE BETA
2.395

F = Failed
S = Suspended

F-418SC-1-R100

TABLE VIII

ENDURANCE TEST RESULTS AND STATISTICAL ANALYSIS

FT. BELVOIR GREASE C[3]

TYPE I TEST - 394K BEARING OPERATING TEMP

Bearing Life - Millions of Revolutions

6.2	F
6.2	F
6.8	F
8.0	F
9.1	F
9.2	F
9.2	F
9.9	F
12.7	F
17.0	S

Bearing Life - Millions of Revolutions

LCL L_{10}	MED L_{10}	UCL L_{10}
2.18	4.33	6.56
LCL L_{50}	MED L_{50}	UCL L_{50}
6.96	9.18	11.96

SLOPE BETA
2.761

F = Failed
S = Suspended

F-4185C-1-R100

TABLE IX

ENDURANCE TEST RESULTS AND STATISTICAL ANALYSIS

FT. BELVOIR GREASE D[3]

TYPE I TEST - 394K BEARING OPERATING TEMP

Bearing Life - Millions of Revolutions

6.5	F
6.9	F
9.0	F
9.1	F
9.9	F
9.8	F
12.1	F
11.2	F
12.7	F
14.6	S
15.8	S

Bearing Life - Millions of Revolutions

LCL L_{10}	MED L_{10}	UCL L_{10}
2.76	5.47	7.78
LCL L_{50}	MED L_{50}	UCL L_{50}
8.36	10.68	13.86

SLOPE BETA
3.169

F = Failed
S = Suspended

TABLE X

ENDURANCE TEST RESULTS AND STATISTICAL ANALYSIS

FT. BELVOIR GREASE E[3]

TYPE I TEST - 394K BEARING OPERATING TEMP

Bearing Life - Millions of Revolutions

2.6	F
3.4	F
3.4	F
4.2	F
4.3	F
4.5	F
5.8	F
7.5	F
8.0	F
10.9	F

Bearing Life - Millions of Revolutions

LCL L_{10} 1.06	MED L_{10} 2.15	UCL L_{10} 3.55
LCL L_{50} 3.69	MED L_{50} 5.10	UCL L_{50} 6.73

SLOPE BETA
2.373

F = Failed
S = Suspended

3.3 SEM Observations Of Cone Rolling Contacts

The rolling contact surfaces of a bearing are subject to some deterioration with use. The magnitude of deterioration is dependent on a number of factors, e.g., operating conditions, environment, and the lubrication characteristic of the grease or oil used. By keeping the major operating parameters constant, as was done in this test series, the degree of surface deterioration is then a function of the aggregate effectiveness of the grease over the total life of the bearing. The severity of distress can range from extremely mild microwear normally associated with good lubrication to that of total exfoliation of the rolling contacts as a consequence of inadequate lubrication.

Accordingly, another important facit of this investigative program was the assessment of the lubrication characteristics of these greases by observing the degree of damage to the original surface morphology after a finite time of operation.

This phase of the investigation was implemented by choosing two bearings of each size from each group of ten bearings which had completed 300 hours of operation or were the longest lived of the group.

3.3.1 Procedure of Examination

Each of the chosen bearings was cleaned and then examined optically at magnifications of up to 30X for evidence of surface distress. On the basis of this examination a typical area on the rolling contact surfaces of each cone was chosen and marked for further examination. This was accomplished by means of an ETEC Autoscan Scanning Electron Microscope (SEM). Each area was examined at magnifications of 250X and 1000X. The area was representative of the amount of surface deterioration present and typified the magnitude of microwear which had occurred after a certain time interval of operation.

The SEM micrographs provide a pictorial representation of the condition of the vital running surfaces and enable a comparison of the anti-wear and lubrication characteristics of the greases being evaluated. However, the reader is cautioned to view the micrographs with care. The surface defects are seen in great contrast and magnitude; and, therefore appear more pronounced than when examined visually. It is noted that visually, some bearings seem to be in good condition and could have run longer. Except for the obvious failures due to large spalls, an auto mechanic probably would not remove them from service. For further reference on the techniques of examining bearing surfaces with the SEM, a definative text has been published which provides many sample scanning electron photomicrographs and discussions of failure types and progression [5].

The degree of microwear occurring can be qualitatively estimated by comparing the SEM micrographs of the run surface with that of a new surface. Generally, if the lines generated by the manufacturing processes remain, the microwear is considered minimal or slight. As the wear process progresses, the lines become less distinct; but as long as some lines are evident the microwear can be considered as being within acceptable limits. When the lines are obliterated, the wear is significant; and the internal geometry can be detrimentally altered. A microspalled surface will eventually generate the exfoliation of larger areas which will ultimately result in the total failure of the bearing surface as shown in Figure 3.

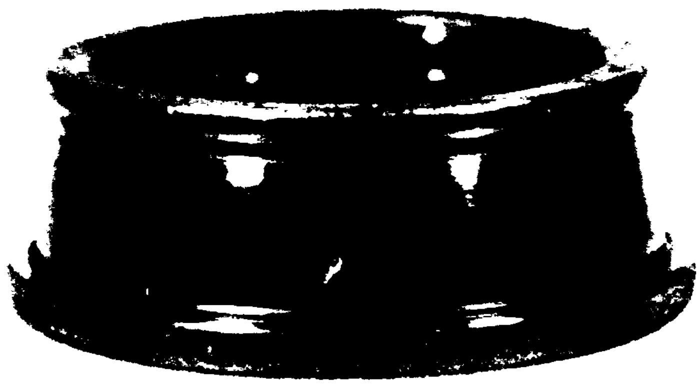
Figure 4 shows SEM micrographs of the rolling contact surfaces of a new cone at 250X and 1000X. The micrographs depict the morphological aspect of a ground and tape honed surface according to current manufacturing practice. Some of the marks or lines are those produced during the grinding process. The high asperities normally associated with a ground surface have been removed by honing. Superimposed lines running at a slight angle to the grinding lines are those produced by honing. Although at this high magnification, the surfaces appear rough, in reality, the roughness is less than 8 microinches A.A.

SEM photomicrographs of typical bearings from each grease group are presented in Figures 5 to 14. Where possible unfailed bearings were chosen which had completed 300 hours of operation. In those instances, i.e., Grease E where none of the bearings had completed 300 hours, the longest lived bearings were chosen. In this case, the surfaces shown were debris damaged and/or spalled.

FIGURE 3

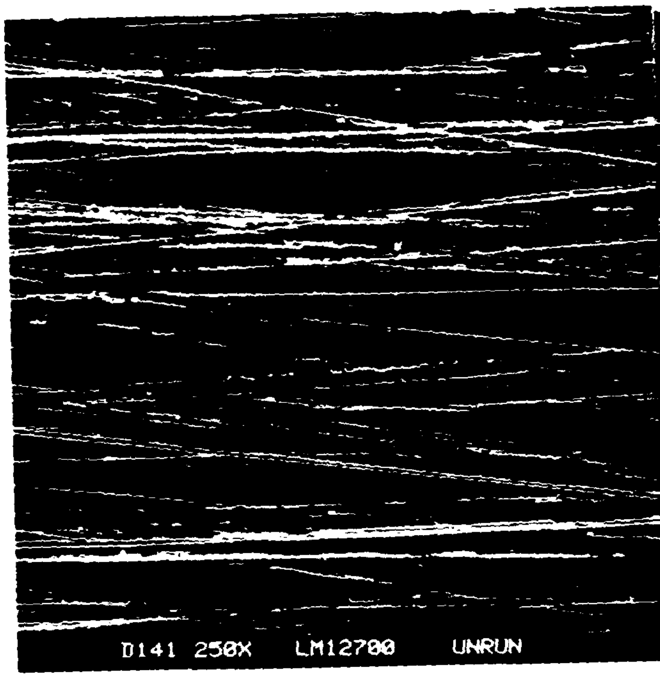
EXAMPLES OF VISIBLE DAMAGE TO CONE ROLLING CONTACT SURFACES

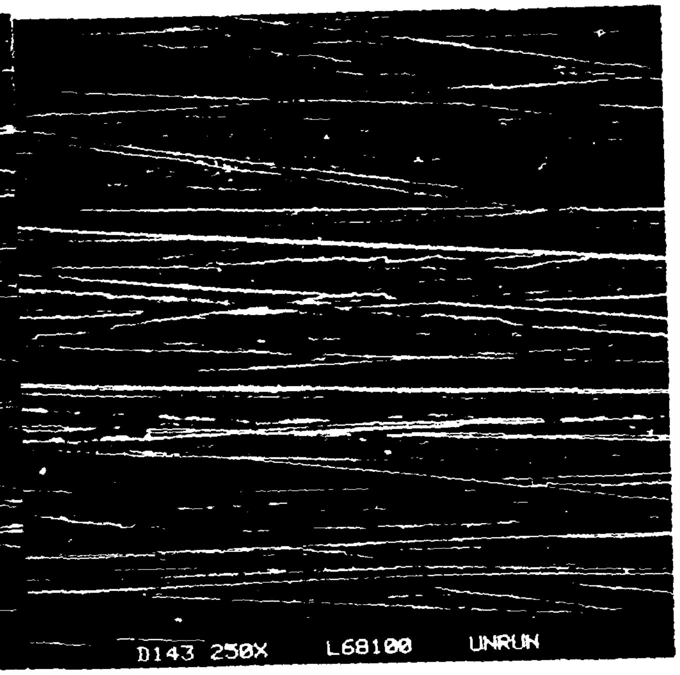
Cone Surface - Macrosurface Distress



Cone Surface - Spall and Macrosurface Distress

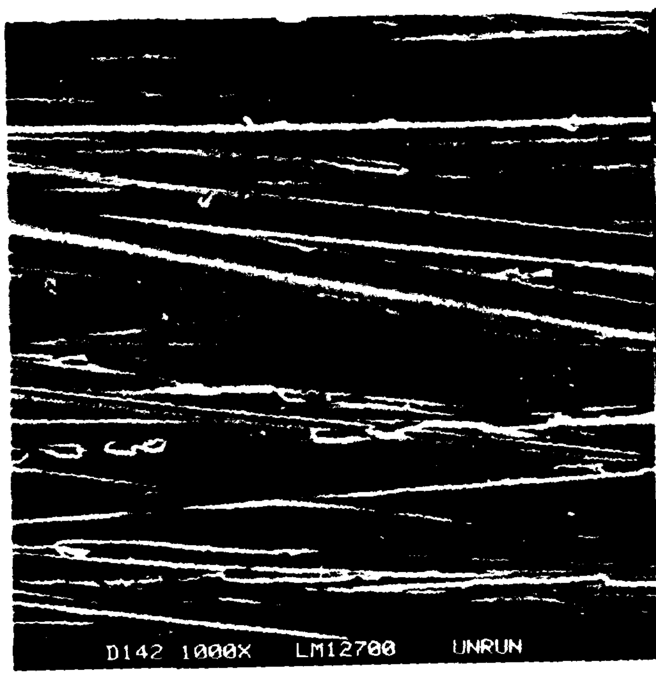
FIGURE 4
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS

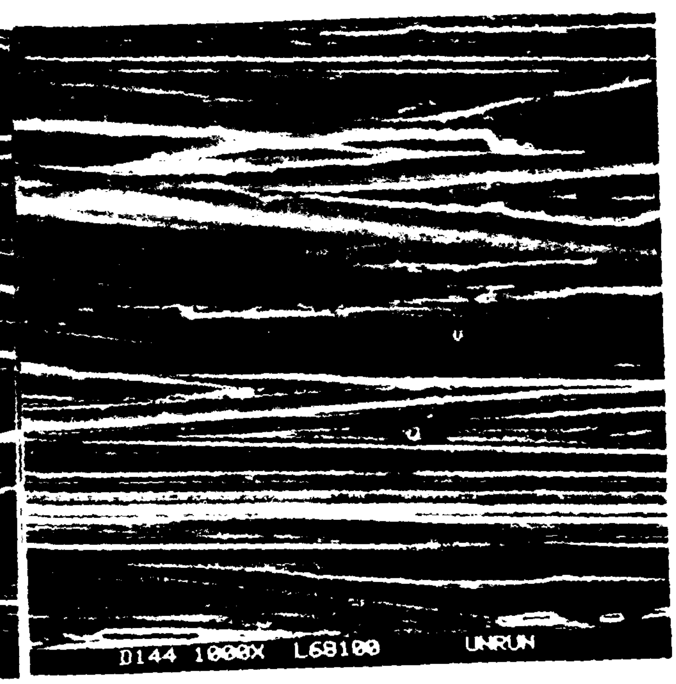




250X

250X





1000X

1000X

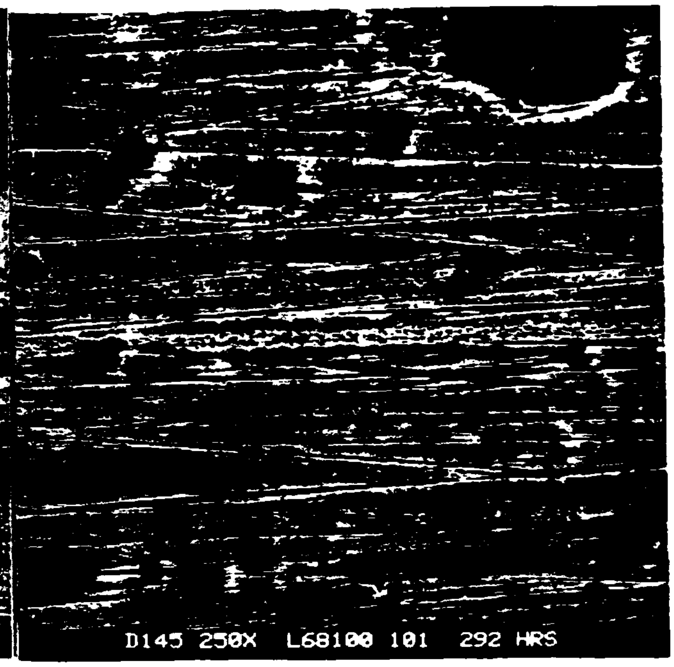
LM12700 (OUTBOARD BRG.)

L68100 (INBOARD BRG.)

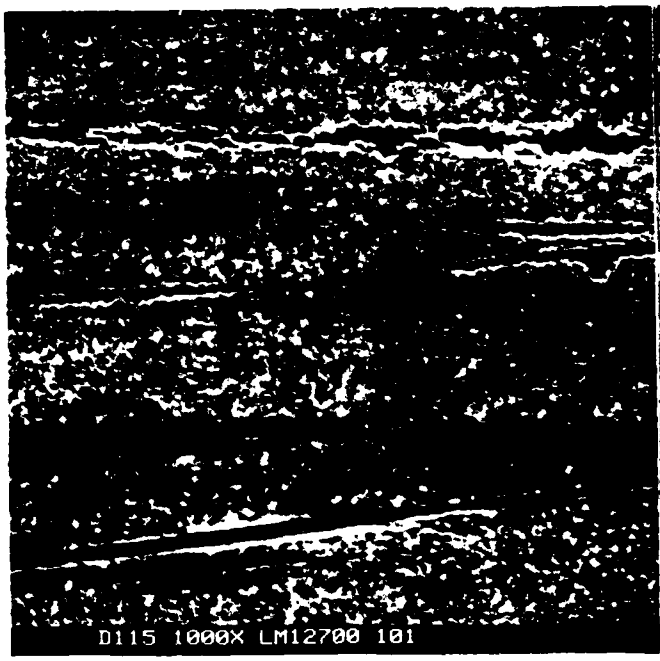
UNRUN CONE ROLLING CONTACT SURFACE

FIGURE 5
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS

250X



250X



1000X

1000X

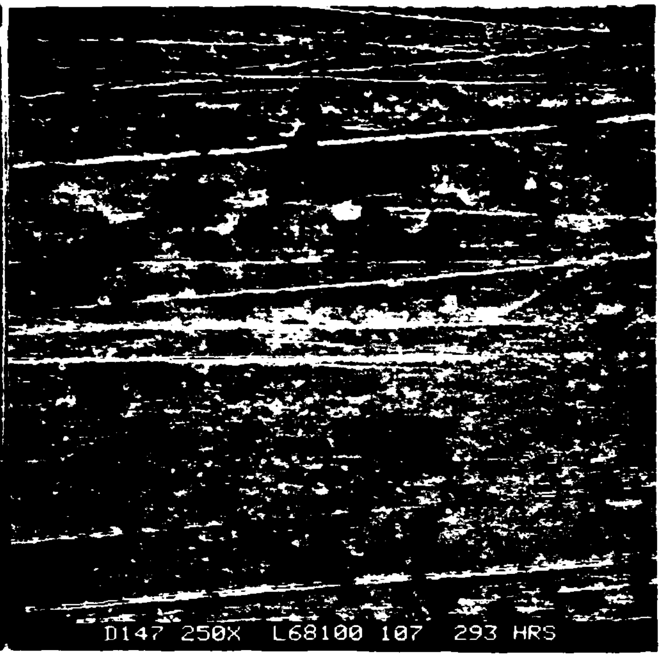
LM12700 (OUTBOARD BRG.) L68100 (INBOARD BRG.)

GREASE A BEARING SET 101

HOURS RUN 292 MIL REVS 14.0

FIGURE 6
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS

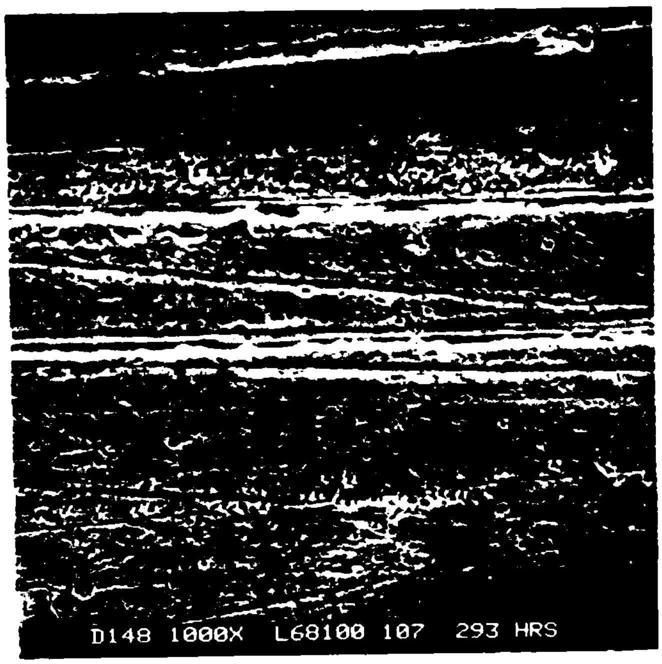
250X



250X

1000X

LM12700 (OUTBOARD BRG.)



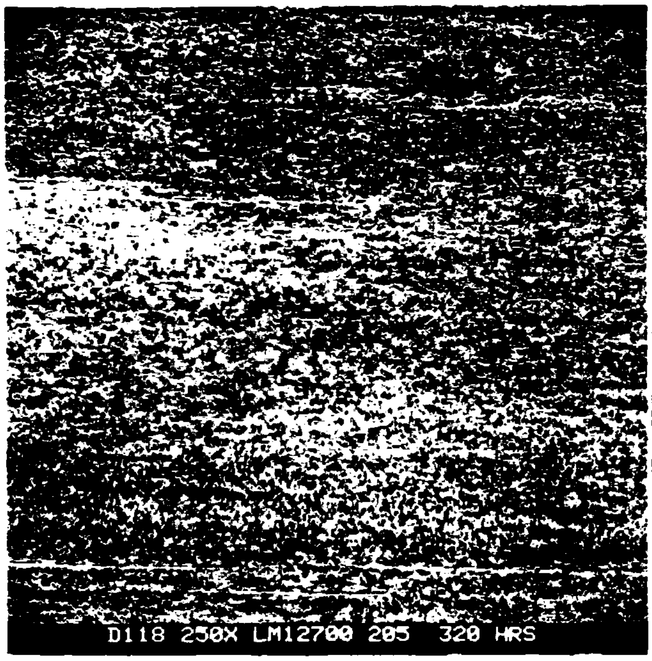
1000X

L68100 (INBOARD BRG.)

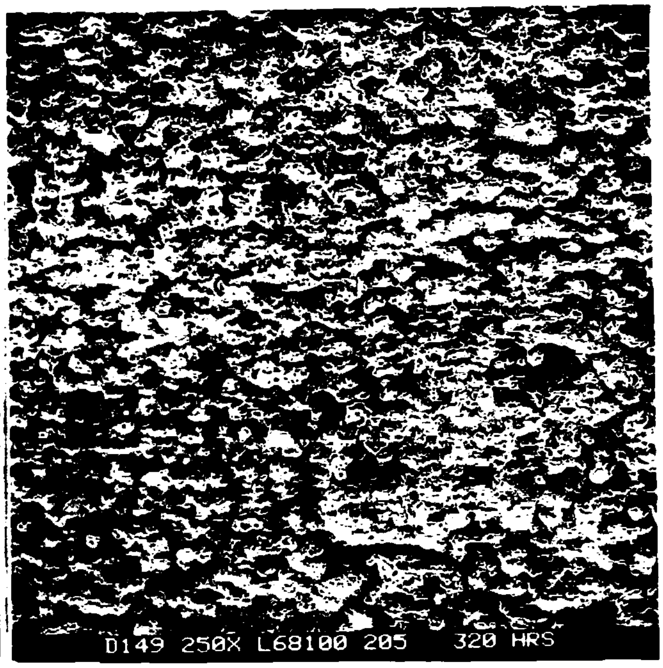
GREASE A BEARING SET 107

HOURS RUN 293 MIL REVS 14.0

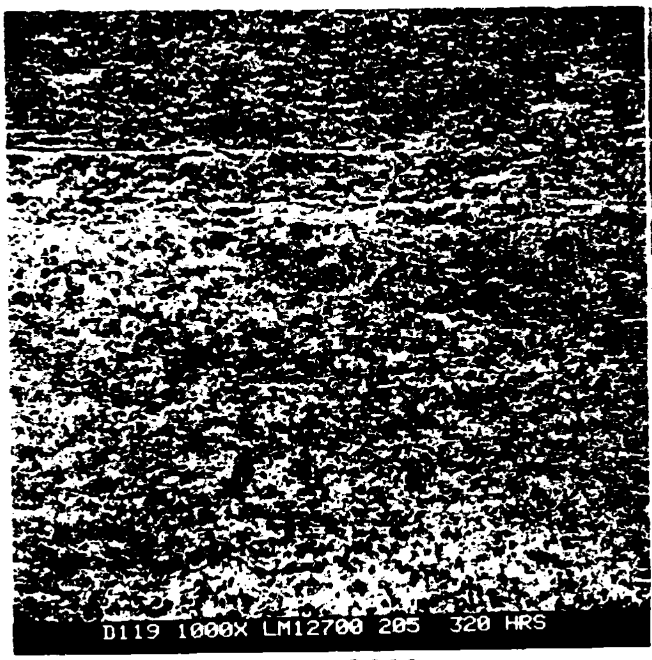
FIGURE 7
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS



250X



250X



1000X

LM12700 (OUTBOARD BRG.)

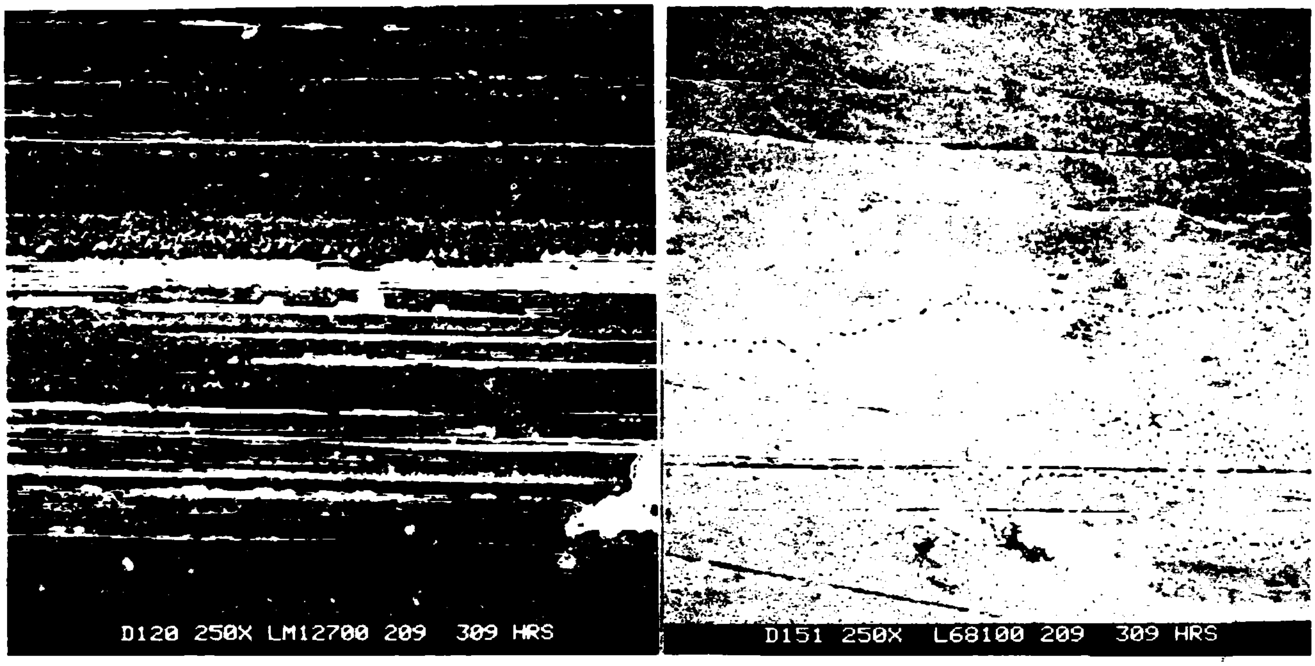
1000X

L68100 (INBOARD BRG.)

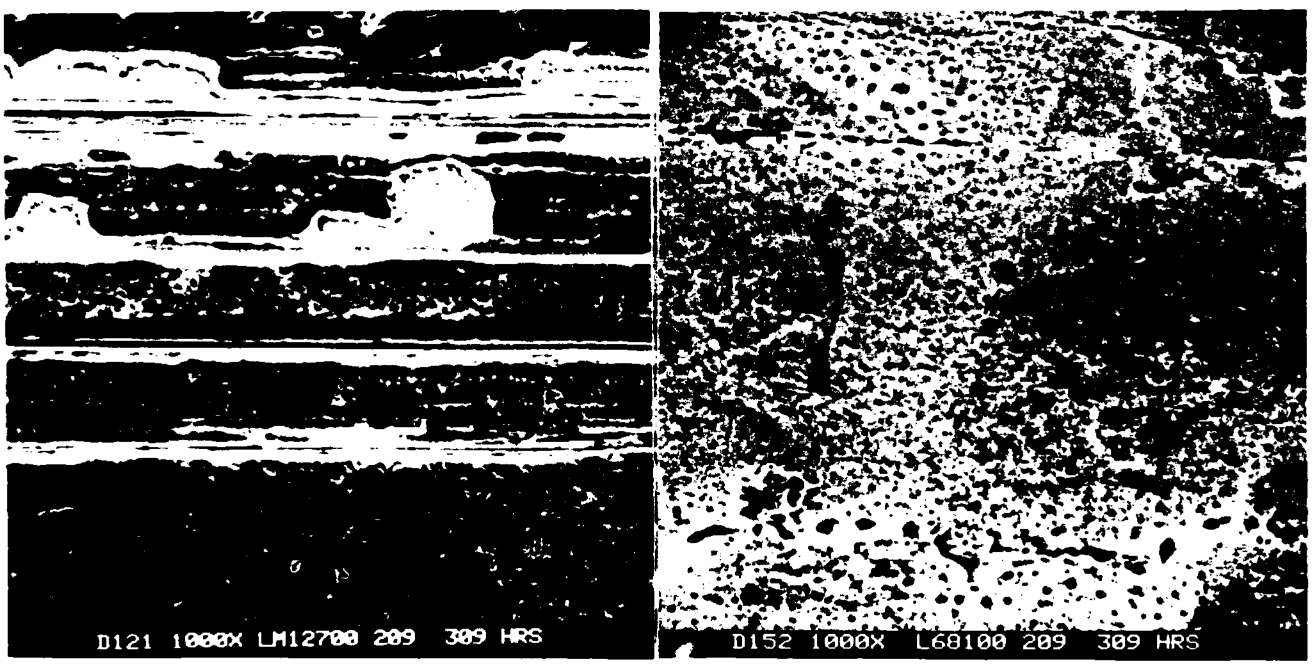
GREASE B BEARING SET 205

HOURS RUN 320 MIL REVS 15.4

FIGURE 8
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS



250X 250X



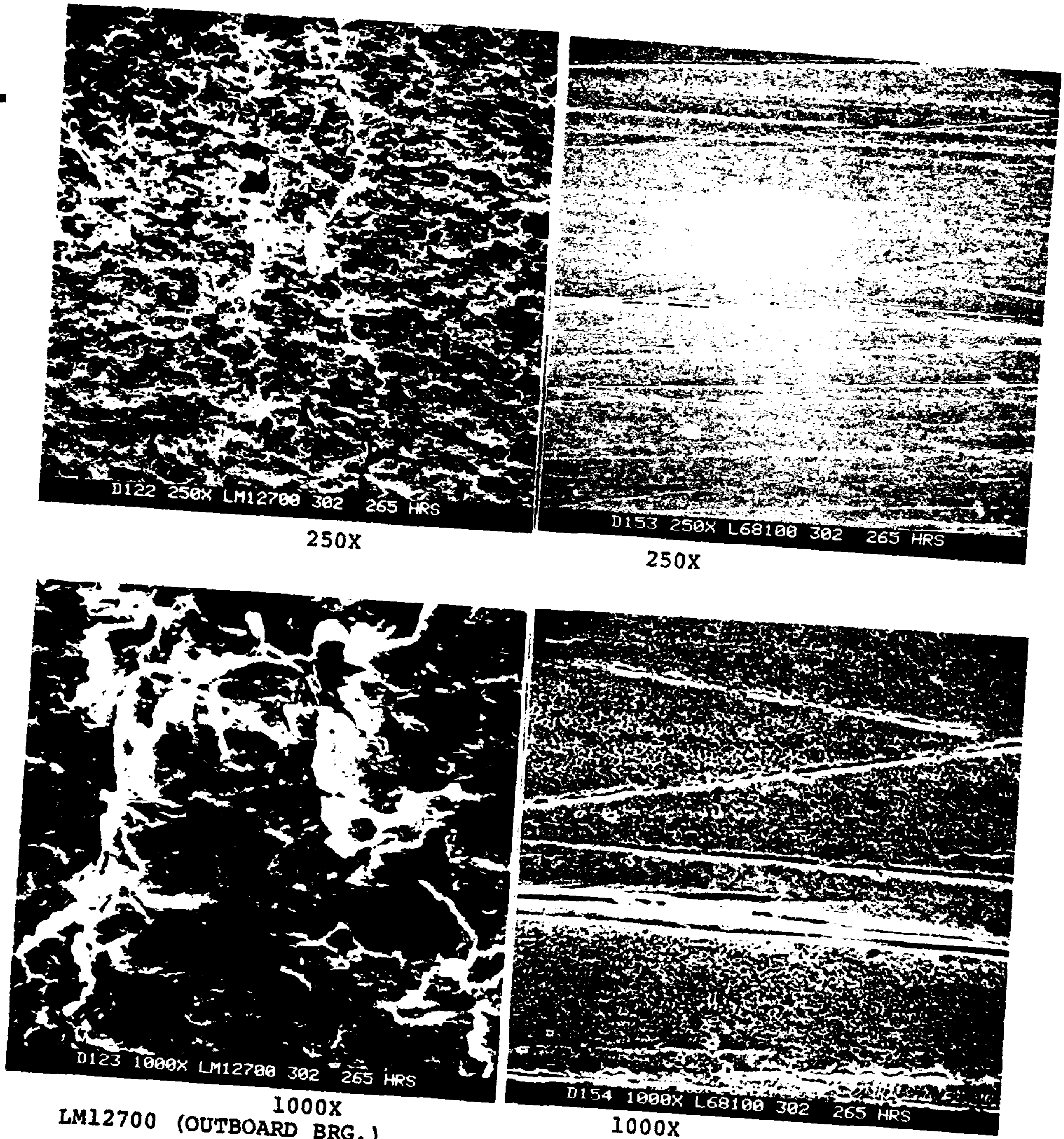
1000X 1000X

LM12700 (OUTBOARD BRG.) L68100 (INBOARD BRG.)

GREASE B BEARING SET 209

HOURS RUN 309 MIL REVS 14.9

FIGURE 9
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS



250X | 250X

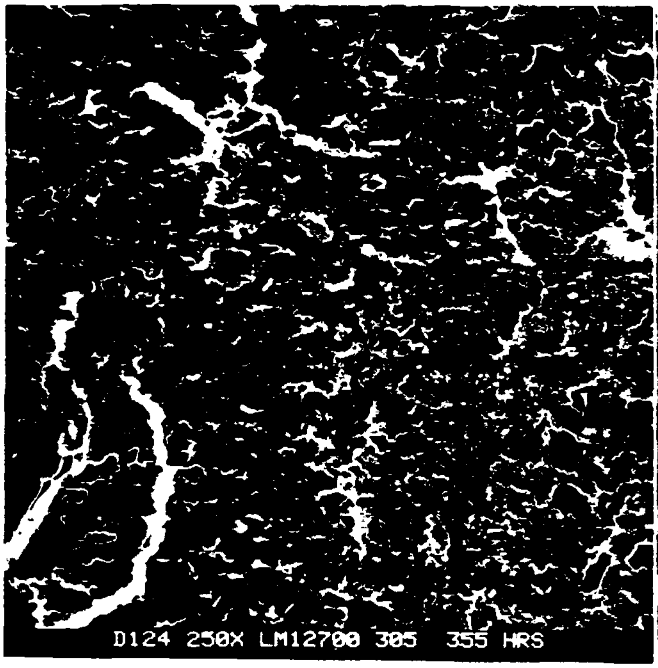
1000X
LM12700 (OUTBOARD BRG.)

1000X
L68100 (INBOARD BRG.)

GREASE C — BEARING SET 302

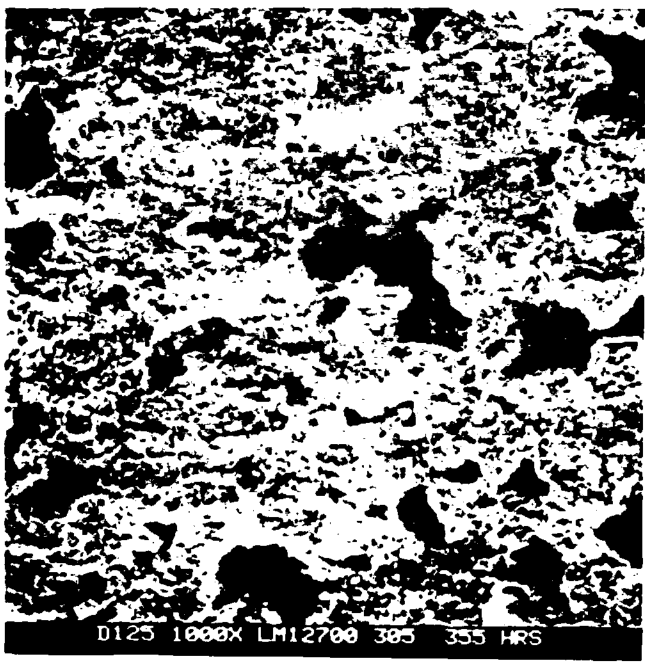
HOURS RUN 265 — MIL REVS 12.7

FIGURE 10
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS



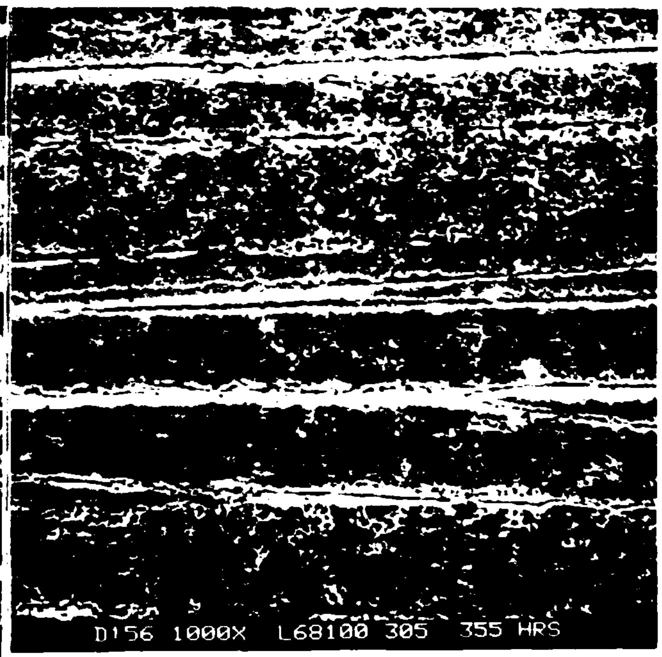
250X

250X



1000X

LM12700 (OUTBOARD BRG.)



1000X

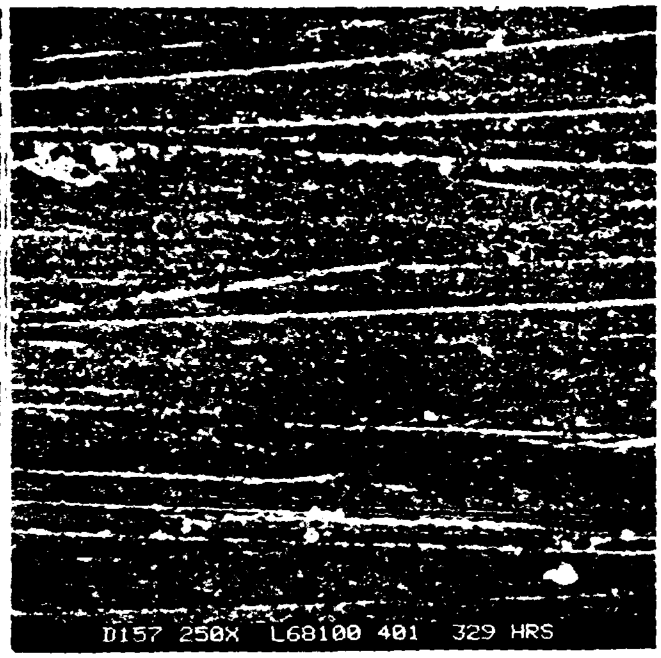
L68100 (INBOARD BRG.)

GREASE C BEARING SET 305

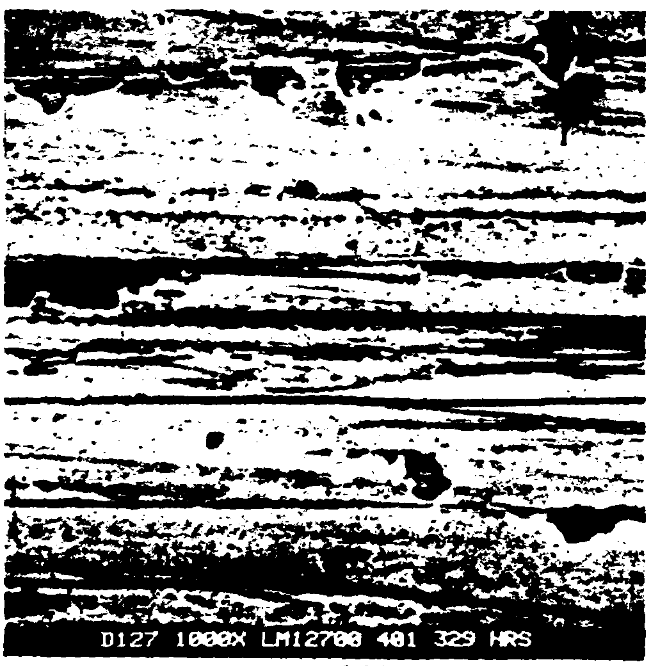
HOURS RUN 355 MIL REVS 17.0

FIGURE 11
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS

250X

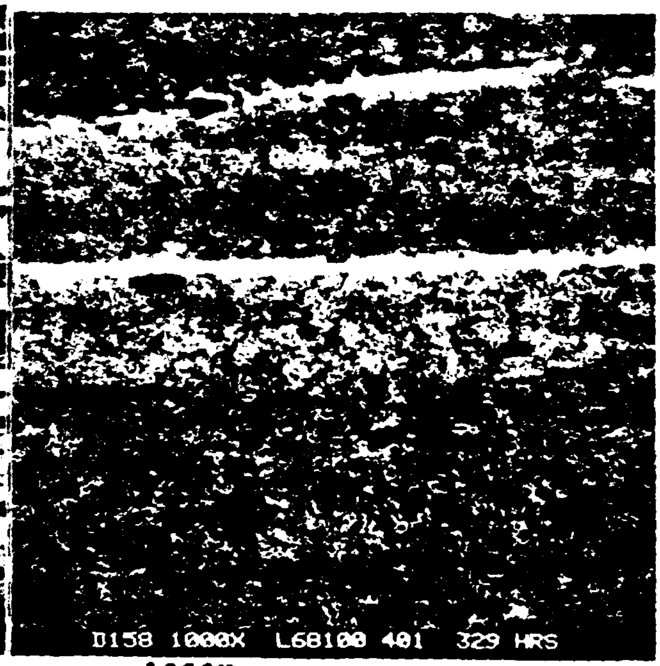


250X



1000X

LM12700 (OUTBOARD BRG.)



1000X

L68100 (INBOARD BRG.)

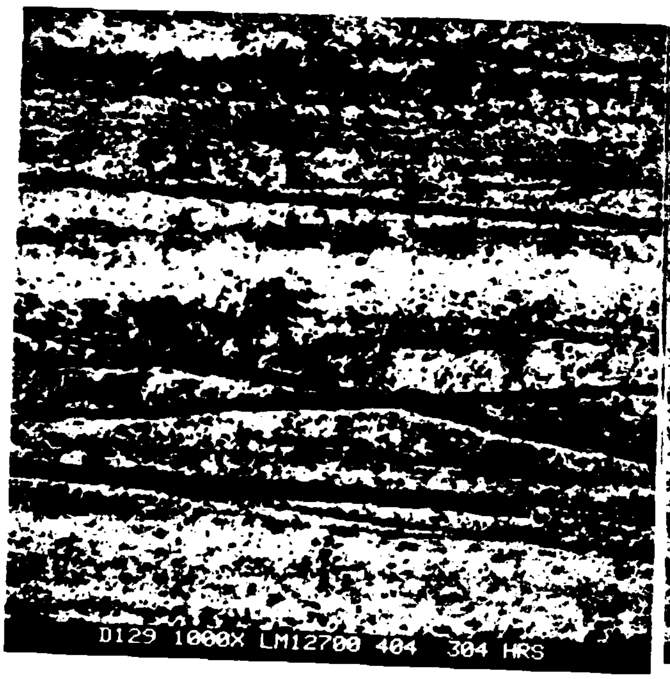
GREASE D   BEARING SET 401

HOURS RUN 329   MIL REVS 15.8

FIGURE 12
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS

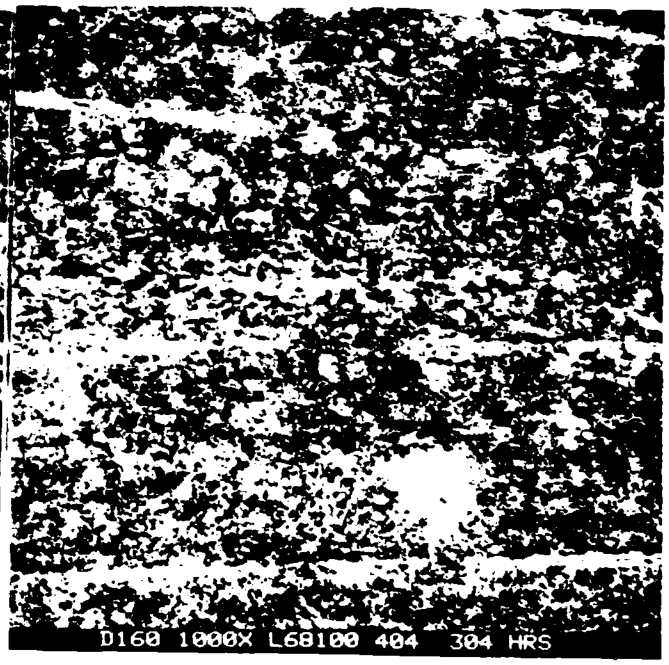
250X

250X



1000X

LM12700 (OUTBOARD BRG.)



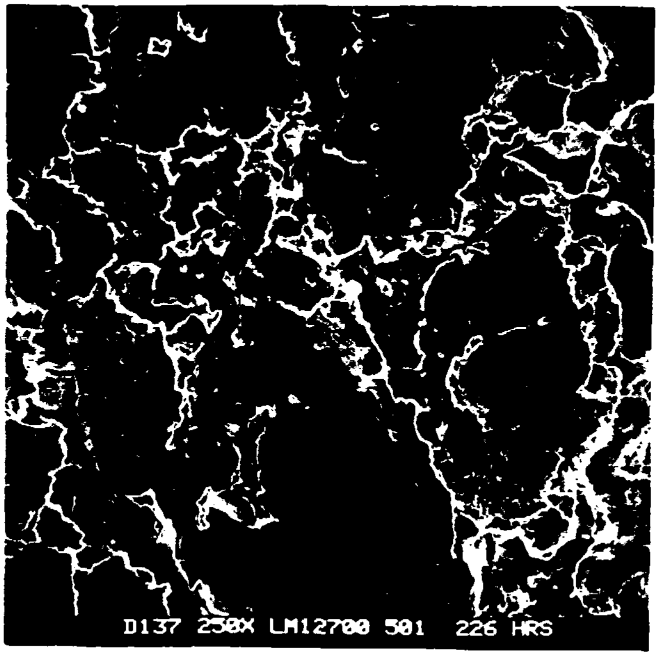
1000X

L68100 (INBOARD BRG.)

GREASE D BEARING SET 404

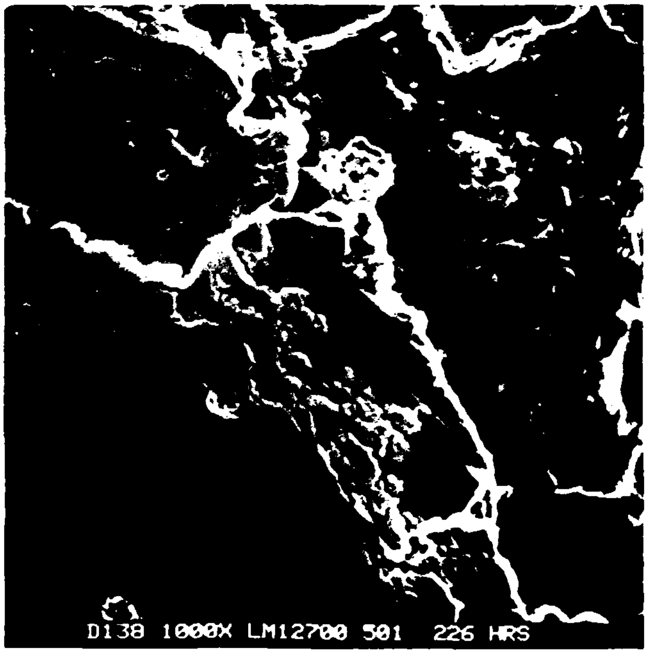
HOURS RUN 304 MIL REVS 14.6

FIGURE 13
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS



250X

250X



1000X

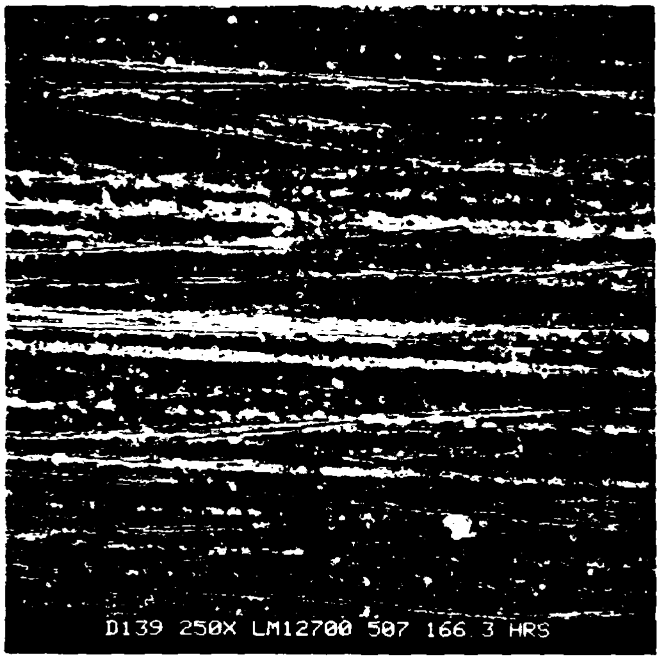
1000X

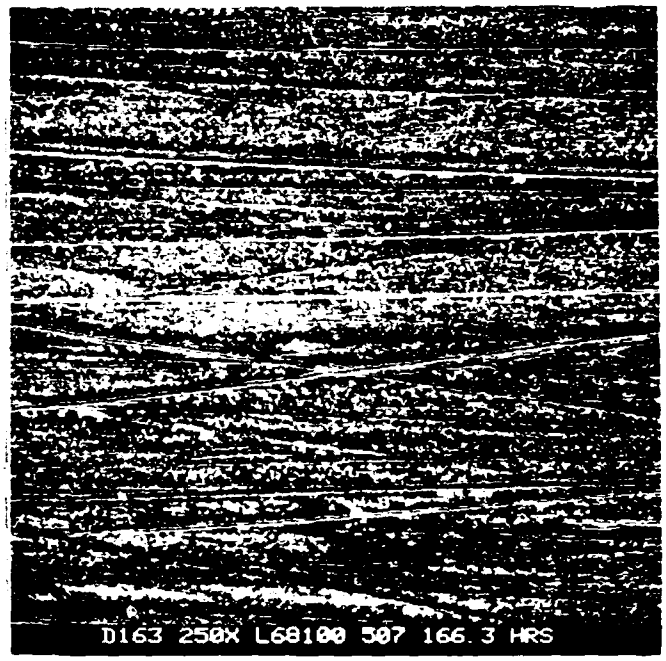
LM12700 (OUTBOARD BRG.)   L68100 (INBOARD BRG.)

GREASE E   BEARING SET 501

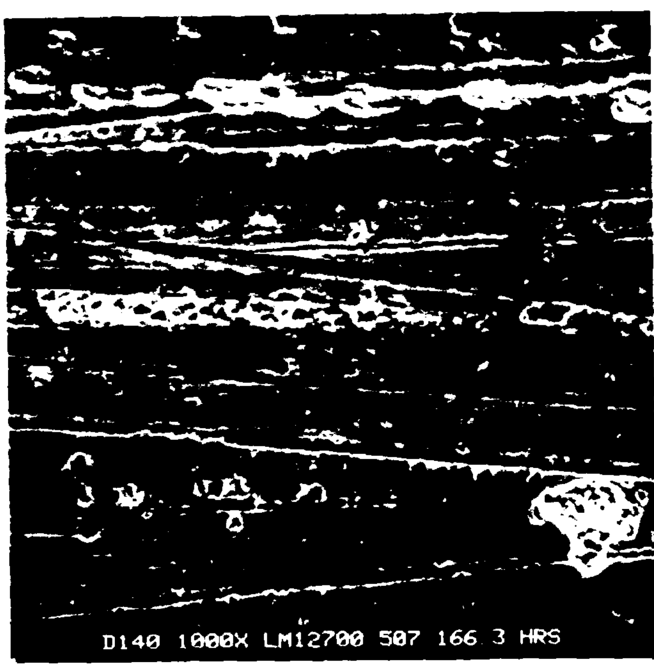
HOURS RUN 226   MIL REVS 10.9

FIGURE 14
POST TEST CONDITION OF TEST BEARINGS
SEM PHOTO MICROGRAPHS





250X 250X



1000X 1000X

LM12700 (OUTBOARD BRG.) L68100 (INBOARD BRG.)

GREASE E BEARING SET 507

HOURS RUN 166.3 MIL REVS 8.0

4.0 DISCUSSION OF TEST RESULTS

4.1 Summary of All Results

Test ratings from the 5 greases evaluated are presented in Tables XI to XV and summarized in Table XVI for all of the greases. The tables document the experimental L_{10} life achieved by the group of test bearings, the post test visual observations of the condition of the residual grease remaining on the bearings, and the condition of the rolling contact surfaces based on visual and SEM examination.

TABLE XI

Experimental Military Lubricating Grease Evaluation - Nondriven Wheel Bearing Application

SUMMARY OF TEST RESULTS

Type I Test: Operating bearing temperature controlled @ 394K

Test Grease: A [3] Light Creamy White Color

Overall Rating: Poor

Experimental L_{10} Life: 2.68 Million Revs.

Basic Performance: Poor

15 of 20 bearings (10 pairs) fatigue spalled, attributed to inadequate lubrication. Both inboard and outboard bearings failed.

Visual Grease Condition: Poor-Fair

Very little usable grease remained in bearings. In most instances grease oxidized considerably. Cage bar surfaces virtually devoid of grease.

Bearing Condition:

Outboard (LM12700) Poor-Fair

Most cones spalled. Some macro spalled and moderately glazed. Bearings rated fair - not visibly damaged but are glazed.

SEM photomicrographs - Cone surfaces have few honing lines indicating moderate wear; and are macro spalled.

Inboard (L68100) Poor-Fair

Both cup and cones spalled. Failures attributed to poor lubrication. Rolling contacts moderately glazed.

SEM photomicrographs - Cone surfaces moderately worn (some lines remain) with surface distress.

TABLE XII

Experimental Military Lubricating Grease Evaluation -
Nondriven Wheel Bearing Application

SUMMARY OF TEST RESULTS

Type I Test: Operating bearing temperature controlled @ 394K

Test Grease: B [3] Light Creamy White Color

Overall Rating: Poor

Experimental L_{10} Life: 4.52 Million Revs.

Basic Performance: Poor

5 of 20 bearings (10 pairs) fatigue spalled, attributed to inadequate lubrication. Mostly inboard bearings failed. Bearings sparsely lubricated and grease greatly oxidized. Some surfaces appear chemically etched.

Visual Grease Condition: Poor

Virtually no grease remained on rolling contacts. Grease on cage surfaces oxidized and had no lubricity.

Bearing Condition:

Outboard (LM12700) Generally Poor

Most bearings dry. Black deposit on rolling contacts. Contacts are brown, microspalled and glazed.

SEM photomicrographs - Most surfaces devoid of honing lines, show wear and microspalled.

Inboard (L68100) Generally Poor

Most bearings dry, with black carbon deposit on rolling contacts. Contacts are brown.

SEM photomicrographs - Most honing lines eliminated indicating considerable wear. Surfaces are profusely damaged.

TABLE XIII

Experimental Military Lubricating Grease Evaluation - Non-driven Wheel Bearing Application

SUMMARY OF TEST RESULTS

Type I Test: Operating bearing temperature controlled @ 394K

Test Grease: C [3] Light Amber Color

Overall Rating: Poor

Experimental L_{10} Life: 4.33 Million Revs.

Basic Performance: Poor

9 of 20 bearings (10 pairs) exhibit fatigue spalls. Virtually all failures are lubricant related. All bearings heat discolored varying degrees. Many tests terminated by high temperature excursions.

Visual Grease Condition: Poor

Most bearings devoid of meaningful lubrication. Grease dry and very oxidized.

Bearing Condition:

Outboard (LM12700) Generally Poor

Rolling contact surfaces severely damaged (macrospalled) and worn. Bearings generally heat discolored indicating high temperature at the rolling contacts at time of failure.

SEM photomicrographs - Cone contacts devoid of honing lines, are severely damaged and worn.

Inboard (L68100) Poor-Fair (For bearings run less than 300 hours). Many bearings dry, and heat discolored. Some appear better than they should since they ran less than 300 hours. (Companion bearing failed).

SEM Photomicrographs: Some honing lines remain, but considerable microsurface distress present indicating poor lubrication.

TABLE XIV

Experimental Military Lubricating Grease Evaluation - Nondriven Wheel Bearing Application

SUMMARY OF TEST RESULTS

Type I Test: Operating bearing temperature controlled @ 394K

Test Grease: D [3] Light Amber Color

Overall Rating: Fair

Experimental L_{10} Life: 5.47 Million Revs.

Basic Performance: Fair

11 of 20 bearings (10 pairs) fatigue spalled caused by inadequate lubrication. Generally, residual grease had some lubricity. Rating spread from poor to fair indicates grease has marginal high temperature capability.

Visual Grease Condition: Fair

Residual grease has some lubricity, but oxidized and dark brown.

Bearing Condition:

Outboard (LM12700) Poor to Fair

Poor rated bearings - spalled rolling contacts and heat discolored.
Fair rated bearings - fairly well lubricated but surfaces are erroded and glazed.
Marginal lubrication caused erratic results.

SEM photomicrographs - Many honing lines remain, but surfaces are eroded (pit marks).

Inboard (L68100) Poor to Fair

Poor rated bearings - spalled and heat discolored.
Fair bearings - some visible signs of distress and glazed.

SEM photomicrographs - Surfaces still have some honing lines but show microdistress and errosion.

TABLE XV

Experimental Military Lubricating Grease Evaluation - Nondriven Wheel Bearing Application

SUMMARY OF TEST RESULTS

Type I Test: Operating bearing temperature controlled @ 394K

Test Grease: E [3] Creamy White in Color

Overall Rating: Poor

Experimental L_{10} Life: 2.16 Million Revs.

Basic Performance: Poor

1 of 20 bearings (10 pairs) spalled. None ran 300 hours. In most tests, thermal imbalance (temperature excursions) terminated run. Bearings sparsely lubricated. Many rolling contacts had black carbonaceous deposits. All failures attributed to inadequate lubrication.

Visual Grease Condition: Poor - Erratic

Outboard bearings - sparsely lubricated. Residual grease dry, black and very oxidized offering no lubrication. Inboard bearings lubricated better in some cases but these had not run the full test time.

Bearing Condition:

Outboard (LM12700) Generally Poor

Most bearings poorly lubricated, show severe surface distress. Contacts coated with black carbonaceous deposit of grease residue.

SEM photomicrographs - Figures 13 and 14 show range of surface distress, from very severe after 226 hours to mild after 166 hours.

Inboard (L68100) Generally Fair (but test hours were very short due to temperature excursions). Rolling contacts in good condition, but run only 1/3 of time.

SEM photomicrographs - Some honing lines remain; however the surfaces show extensive microdistress.

4.2 Rating of Performance

In accordance with the rating system established previously [1 and 2], the current candidate greases have been rated on the basis of the following parameters:

1. The experimental L_{10} life achieved by the group of bearings lubricated by the test grease.

2. The severity of grease deterioration.

3. The effect of the lubricant on the change in rolling contact surface morphology.

Table XVI lists the greases in order of increasing lubrication capability. As shown, the greases have been rated from Poor to Fair as follows:

E, A, C, B and D [all 3]

The low lived bearing-grease systems lubricated with Greases E, A, C and B [3] had excessive surface damage. Ultimately the microspalls observed nucleated into larger spalls which caused the final total destruction of some bearings. The bearings lubricated with Grease D [3] exhibited less distress. However, the extent of surface deterioration after only 300 hours of operation or 14.4 million revolutions was significant. The magnitude of damage probably compromised bearing life.

Therefore, according to the performance characteristics indicated, Greases E and A are inferior to Greases C and B and Grease D is the best of the five lubricants tested. Even so, the lubrication capability of Grease D appears to be marginal at the high temperature conditions run, and therefore may prove to be inadequate under the extreme and demanding environmental operational conditions expected to be encountered in army vehicle service.

TABLE XVI

Summary of Grease Evaluation

Test Grease	Experimental L_{10} Life Million Revs.	Slope Beta	No. of Failures (a)	Post Test Observations Rating: Performance	Grease Condition	Bearing Condition
E [3]	2.16	2.37	10	Poor	Poor	Poor
A [3]	2.68	1.50	10	Poor	Poor	Poor
C [3]	4.33	2.76	9	Poor	Poor	Poor
B [3]	4.52	2.39	8	Poor	Poor	Poor
D [3]	5.47	3.17	8	Fair	Fair	Fair

Theoretical 11.3 (b)

(a) Note: The L_{10} life was based on the lives of 10 pairs of bearings. Previously 20 pairs of bearings were run.

(b) The theoretical life is based on the life a well lubricated bearing is likely to achieve based on the calculations shown in Appendix I.

4.3 Comparison With Previous Grease Results

The five greases tested herein are compared to those tested previously in Table XVII. The tabulation lists all of the greases evaluated in all three contracts in the order of improving performance. As shown, the experimental L_{10} life of Greases E [3] and A [3] were among the lowest lived of all greases evaluated. Greases C [3] and B [3] were slightly longer lived, but still were rated POOR since the condition of the greases and bearings were not satisfactory. Grease D [3], the best of the five current test greases was rated FAIR. This places the lubricant in a group that had slighly better overall performance characteristics for the conditions tested than the rest of the current candidate greases.

In reality, none of the five greases exhibited lubrication characteristics considered to be adequate for the test conditions run, and especially at the operational temperature of 394K (121°C). None, totally equalled the good performance of Greases C [1], D [1] and E [1] tested previously which are considered to be premium greases.

On the basis of these tests, the current greases evaluated exhibit minimal lubrication capability under abnormally high operational temperatures; and therefore may be unsuited for some aspects of the application intended. These greases however, are considered to be equivalent or slightly better than the current wheel bearing greases A [1] and B [1] tested previously.

TABLE XVII

Summary of All Grease Evaluation
Programs 1, 2 and 3

Type I - Elevated Temperature Test Condition (394 K)

Test Grease	Experimental L_{10} Life Million Revs.	Slope Beta	No. of Failures/ Brgs. Tested	Post Test Observations Rating: Performance	Grease Condition	Bearing Condition
H [2]	< 2.4	5.00	5/6	Very Poor	Poor	Very Poor
B [1]	1.42	1.52	20/20	Poor	Poor	Poor
A [1]	1.68	1.96	20/20	Poor	Poor	Poor
E [3]	2.16	2.37	10/10	Poor	Poor	Fair
A [3]	2.68	1.50	10/10	Poor	Poor	Poor
C [3]	4.33	2.76	9/10	Poor	Poor	Poor
B [3]	4.52	2.39	8/10	Poor	Poor	Poor
G [2]	4.39	2.88	16/20	Fair	Fair	Poor
F [1]	4.69	2.22	15/20	Fair	Fair	Fair
D [3]	5.47	3.17	8/10	Fair	Fair	Fair
C [1]	5.81	3.35	14/20	Good	Good	Good
D [1]	6.18	1.87	8/20	Very Good	Very Good	Very Good
E [1]	15.97	1.33	2/20	Excellent	Excellent	Excellent

[1] Contract DAAK70-77-C-0034
[2] Contract DAAK70-79-C-0213
[3] Contract DAAK70-83-C-0063

Theoretical L_{10} life of the bearing system is 11.3 million revolutions.

5.0 PRACTICAL APPLICATION OF RESULTS

The ability of a grease to lubricate a tapered roller bearing operating in the demanding environment of an automotive non-driven wheel hub especially that of Army vehicles is of paramount importance.

To assure the integrity of a vehicle and to extend its service life the schedule of maintenance includes the periodic servicing of the wheel hub bearings. Under normal operating conditions, general commercial automotive practice dictates that wheel bearings should be regreased every 64,000 kilometers. This regreasing interval is then reduced if the vehicle is operated under adverse conditions, i.e., off the road. Military vehicle maintenance practice conforms to these limitations. Road use vehicles are regreased following commercial recommendations, while off the road field vehicles have regrease intervals ranging from 2,000 to 20,000 kilometers. Therefore, it is important that the service life of a grease be known in order to comply with minimum regreasing schedule requirements.

As a consequence, the suitability of a candidate grease, proported to have superior performance capability, should be based on the premise that it not only provide adequate lubrication, but that through its use, the regreasing interval can be extended in order to reduce maintenance time and costs.

The service life of a candidate grease may be predicted by comparing its performance in a laboratory environment with that of greases now used to lubricate wheel bearings and which conform to military specifications. Grease performance can be predicated on the life achieved in a hostile environment, and the condition of the grease and bearing running surfaces at the conclusion of the test.

Even though the rigorous operational conditions imposed by this laboratory test have substantially reduced the potential life of the bearing-grease system, a lubricants efficacy can be assessed by comparing the life achieved with that of a baseline grease having known performance characteristics. To facilitate the practical application of these data for automotive use, the L_{10} life of each grease in millions of revolutions given in Table XVI, has been expressed in terms of kilometers of operation in Table XVIII.

Greases A [1] and B [1] were chosen as a baseline for the comparison of candidate greases. These two greases which had been tested previously, are used to lubricate wheel bearings, and conform to military government grease specification MIL-G-10924C.

The relative functional capability of a candidate grease can be judged by comparing the lives achieved by the candidate and baseline greases. Assuming that the ratio of the lives is predictive of a candidate greases performance in a similar service environment, it is suggested that consideration be given to adjusting the relubrication interval accordingly. For instance, if the life ratio is two, one might consider extending the regreasing interval twofold.

However, this amount of increase is probably optimistic at this time. Until army field service data can be provided, statistically examined and correlated with laboratory data, the regreasing interval of a grease whose life approaches the theoretical life of the bearing system can be conservatively extended 100 to 150% over that now practiced with a baseline grease for off-the-road vehicles. With experience and correlative army field data it may be possible to extend the regreasing interval still further with a premium quality grease.

TABLE XVIII

Comparison of Test Grease Performance and Potential Increase in Regreasing Interval

Grease Tested	Estimated Median L_{10} Life Kilometers of Operation*		Ratio of Average Life Baseline Greases to Candidate Greases
A. Baseline Greases Conforming to MIL-G-109 24C			
B [1]	3,100	3,400	1.0
A [1]	3,700		
B. Candidate Greases			
E [3]	4,600		1.3
A [3]	5,900		1.7
C [3]	9,200		2.7
B [3]	9,600		2.8
D [3]	11,000		3.4
C. Theoretical*	24,000		7.0

* Based upon a truck tire rolling radius of 0.341 m (13.75")

6.0 CONCLUSIONS

The relative performance characteristics of five automotive type non-driven wheel bearing greases have been assessed in a laboratory environment according to the procedures developed in a previous study [1]. On this basis, the following conclusions have been drawn.

1. None of the five greases exhibited markedly superior lubrication characteristics than several of the greases tested previously.

2. Greases E [3] and A [3] exhibit equivalent lubrication capabilities and appear to be equivalent to Greases A [1] and B [1] tested previously which conform to MIL-G-10924C and are used to lubricate Army vehicles. Greases C [3] and B [3] are somewhat better and Grease D [3] performed the best of the five.

3. Under the high temperature environment tested, the first four greases operated erratically, and were subject to unpredictable temperature excursions indicating a serious lubrication deficiency.

   Grease D [3], had marginal lubrication characteristics; and therefore may not be a good "greased-for-life" candidate of Army vehicles expected to operate under rigorous environmental and extreme temperature conditions. However, since it permitted longer operation than the two greases now used, it may be possible to extend the relubrication interval.

7.0 PROPOSED WORK

Most Army type vehicles never realize their full life potential mileage wise since they are stored until needed. Even so, they must be maintained to assure military readiness. One of the maintenance requirements is the periodic relubrication of wheel bearings. Current practice dictates a rather short time interval for off-the-road type vehicles. When considering the life potential of some premium greases now available, the regreasing interval now practiced by the military seems unreasonably short.

Currently, the automotive industry is lubricating some non-driven wheels for the life of the bearing package. The so called "hub bearing" consisting of a sealed bearing unit is such a device. Although the initial cost of the premium grease used is more than that of conventional lubricants, the costs are less over the long run since relubrication costs are eliminated. Another benefit is that the chance of damaging the bearings and seals of a conventional wheel, when disassembling the wheel hardware to repack the bearings, is eliminated.

While the concept of a greased for life bearing-grease package is attractive for future military vehicles, realistically it is optimistic for current vehicles. However, the regreasing interval can be extended through the use of improved lubricants.

The useful life of a grease is dictated by many factors, some of which depend upon its chemistry. Obviously, a grease should not only be able to withstand the loads imposed at the bearing rolling and sliding contact surfaces, under the temperature extremes the vehicle is expected to operate in, but it must also be resistive to oxidation and provide protection against rust while the vehicle is in storage.

Considering the cost differential between a conventional wheel bearing grease and that of a premium type, and the costs incurred to regrease a wheel bearing, the later costs are far greater. Consequently, in the long run the use of a premium grease would be more cost effective. Also, by extending the relubrication interval, the likelihood of damaging the wheel bearings over the service life of the vehicle is diminished.

Premium greases are now available, and are used by major automotive manufacturers to extend the life of wheel bearings. Therefore, it is proposed that a comprehensive program be initiated which is aimed at the evaluation of available commercial grease candidates or new greases that will function as required for the life of the bearing system.

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APPENDIX I

Method of Calculation to Determine the L_{10} Life of the Test Bearing System

The L_{10} life of the two bearing system employed as calculated here in is based upon formulas and methodology concepts currently in use by the bearing industry [6].

The test conditions employed were:

1. Test Bearing Specimens

   Outboard - LM12749/LM12710 = Brg. 1
   Inboard - L68149/L68110 = Brg. 2

2. Applied Radial Load - 8.34 Kn (1875 lbs.) Applied at a distance of 45.847 mm (1.805 in.) from the outboard bearing pressure center (See Figure 1).

3. Thrust Load - 2.49 Kn (560 lbs.) Applied 30% of the time at a distance of 34.163 cm (13.45 in.) from the horizontal axis of the bearing centerline.

4. Speed - 800 rpm

5. Distance between the outboard bearing and inboard bearing pressure centers is 70.536 mm (2.777 in.).

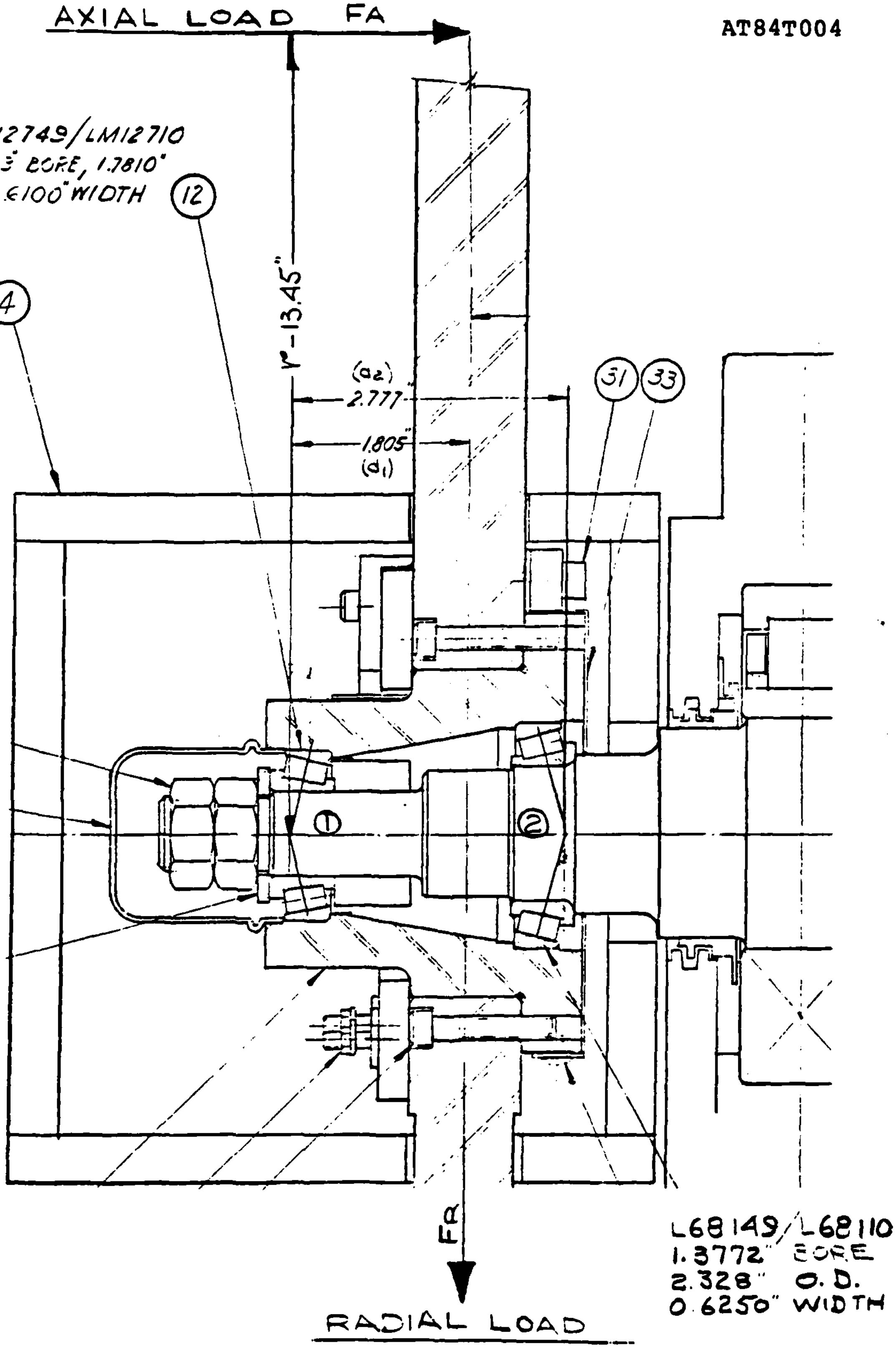

Figure 1
Location of Applied Forces

LIST OF SYMBOLS AND TERMS

L_{10} = Is the life 90% of the bearings are expected to exceed

P = Equivalent Load

Fr = Radial Force on Bearing

FR = Applied Radial Load

Fa = Applied Force on Bearing

FA = Applied Axial Load

Y = Thrust Factor From Bearing Catalog

d_1 = Distance From an Outboard Bearing Pressure Center to FR

d_2 = Distance Between Outboard and Inboard Bearing Pressure Centers

r = Distance Between Horizontal Bearing Axis and F_A

T_r = Induced Thrust Force Due to Applied Radial Force

C = Industrial Radial Load Rating (Catalog)

[illegible] = Constant 3.86. Whenusing the published Industrial Load Rating, it is necessary to convert from a life basis of 90×10^6 revs to a life basis of 1×10^6 revs by multiplying the industrial rating by 3.86.

N = Bearing Speed rpm

The equivalent load P on which the life formula

$$L_{10} = \left(\frac{C}{P}\right)^{10/3}$$

is based upon was calculated from the accumulated forces on the system occurring from the application of (a) radial load only and (b) the combined radial and axial loads as the result of the moment caused by the application of a force at the tire radius.

The determination of P for the first condition for straight radial load is based upon the loads applied to each individual bearing determined as follows:

First Condition - Straight Radial Load Only

$$\Sigma M_1 = 0 \qquad \text{(See Figures 34)}$$

$$FR_2 = \frac{d_1(FR)}{d_2} = \frac{1.805(1875)}{2.777} = 1218 \text{ lbs.}$$

Thrust force induced by Fr_2 force.

$$T_2 = \frac{0.47\ Fr_2}{Y_1} = \frac{0.47(1218)}{1.4} = 409 \text{ lbs.}$$

$$Fr_1 = \frac{d_2-d_1}{d_2}(FR) = \frac{2.777-1.805(1875)}{2.777} = 656 \text{ lbs.}$$

$$T_1 = \frac{0.47\ Fr}{Y_2} = \frac{0.47(656)}{1.91} = 161 \text{ lbs.}$$

Then:

$$P_2 = 1218 \text{ lbs.}$$

$$P_1 = 0.4\ Fr_1 + Y\ (T_2)$$
$$= 0.4\ (656) + 1.91\ (409) = 1044 \text{ lbs.}$$

Second Condition - Sum of Radial, Axial and Moment Loads

$$\Sigma M_1 = 0$$

$$Fr_2 = \frac{d_1(FR + r(FA))}{d_2} = \frac{1.805(1875) + 13.45(560)}{2.777} = 3931 \text{ lbs.}$$

$$T_2 = \frac{0.47(3931)}{1.4} = 1319 \text{ lbs.}$$

$$Fr_1 = Fr_2 - FR = 3931 - 1875 = 2056 \text{ lbs.}$$

$$T_1 = \frac{0.47(2056)}{1.91} = 506 \text{ lbs.}$$

The applied force FA = 560 lbs.

Then:

$$P_2 = 3931 \text{ lbs.}$$

$$P_1 = .4\ (2056) + 1.91\ (1319-560) = 2273 \text{ lbs.}$$

Since the loads on the bearings are applied cyclically i.e., the axial load is applied only 30% of the time and the radial force is constant, the equivalent load P_Q for each of the bearings must be calculated according to the cubic mean value established for the loads applied at each time interval.

In this case:

$$P_Q = \left[0.7\ (P_{1st\ condition})^{10/3} + 0.3\ (P_{2nd\ condition})^{10/3}\right]^{0.3}$$

Accordingly:

$$P_{Q_2} = \left[0.7(1218)^{10/3} + 0.3(3931)^{10/3}\right]^{0.3} = 2777 \text{ lbs.}$$

$$P_{Q_1} = \left[0.7(1044)^{10/3} + 0.3(2273)^{10/3}\right]^{0.3} = 1663 \text{ lbs.}$$

And:

$$L_{10} = \left[\frac{C(2)}{P_Q}\right]^{10/3} = \left[\frac{C(3.86)}{P_Q}\right]^{10/3} \frac{10^6}{60(N)} = \text{Hours}$$

$$L_{10_2} = \left[\frac{1610(3.86)}{2777}\right]^{10/3} \frac{10^6}{60(800)} = 304 \text{ Hours}$$

$$L_{10_1} = \left[\frac{1280(3.86)}{1663}\right]^{10/3} \frac{10^6}{60(800)} = 784 \text{ Hours}$$

The life of the system i.e., the two bearings is

$$\frac{1}{L^e} = \frac{1}{(L_1{}^e)} + \frac{1}{(L_2{}^e)}$$

where $e = 1.125$

Therefore:

$$\frac{1}{L^e} = \frac{1}{(304)^{1.125}} + \frac{1}{(784)^{1.125}} = \frac{1}{622} + \frac{1}{1804}$$

$$\frac{1}{L^e} = 0.0016 + 0.00055 = 0.00216$$

$$L^{1.125} = 463$$

$L = 234$ Hours or 11.3×10^6 revs.

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